INTERGOVERNMENTAL PANEL ON climate change

GLOBAL WARMING OF 1.5 °C

an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

Summary for Policymakers

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Summary for Policymakers

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Introduction

This report responds to the invitation for IPCC '... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policy Makers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5°C and for the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the report.

[1] Decision 1/CP.21, paragraph 21.

[2] The assessment covers literature accepted for publication by 15 May 2018.

[3] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5.

A. Understanding Global Warming of 1.5°C[4]

A1. Human activities are estimated to have caused approximately 1.0°C of global warming[5] above pre-industrial levels, with a *likely* range of 0.8°C to 1.2°C. Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) {1.2, Figure SPM.1}

A1.1. Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (*likely* between 0.75°C and 0.99°C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely* range). Estimated anthropogenic global warming is currently increasing at 0.2°C (*likely* between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (*high confidence*). {1.2.1, Table 1.1, 1.2.4}

A1.2. Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2}

A1.3. Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.3.1, 3.3.2, 3.3.3}

A.2. Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are *unlikely* to cause global warming of 1.5°C (*medium confidence*) {1.2, 3.3, Figure 1.5, Figure SPM.1}

A2.1. Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are *unlikely* to cause further warming of more than 0.5°C over the next two to three decades (*high confidence*) or on a century time scale (*medium confidence*). {1.2.4, Figure 1.5}

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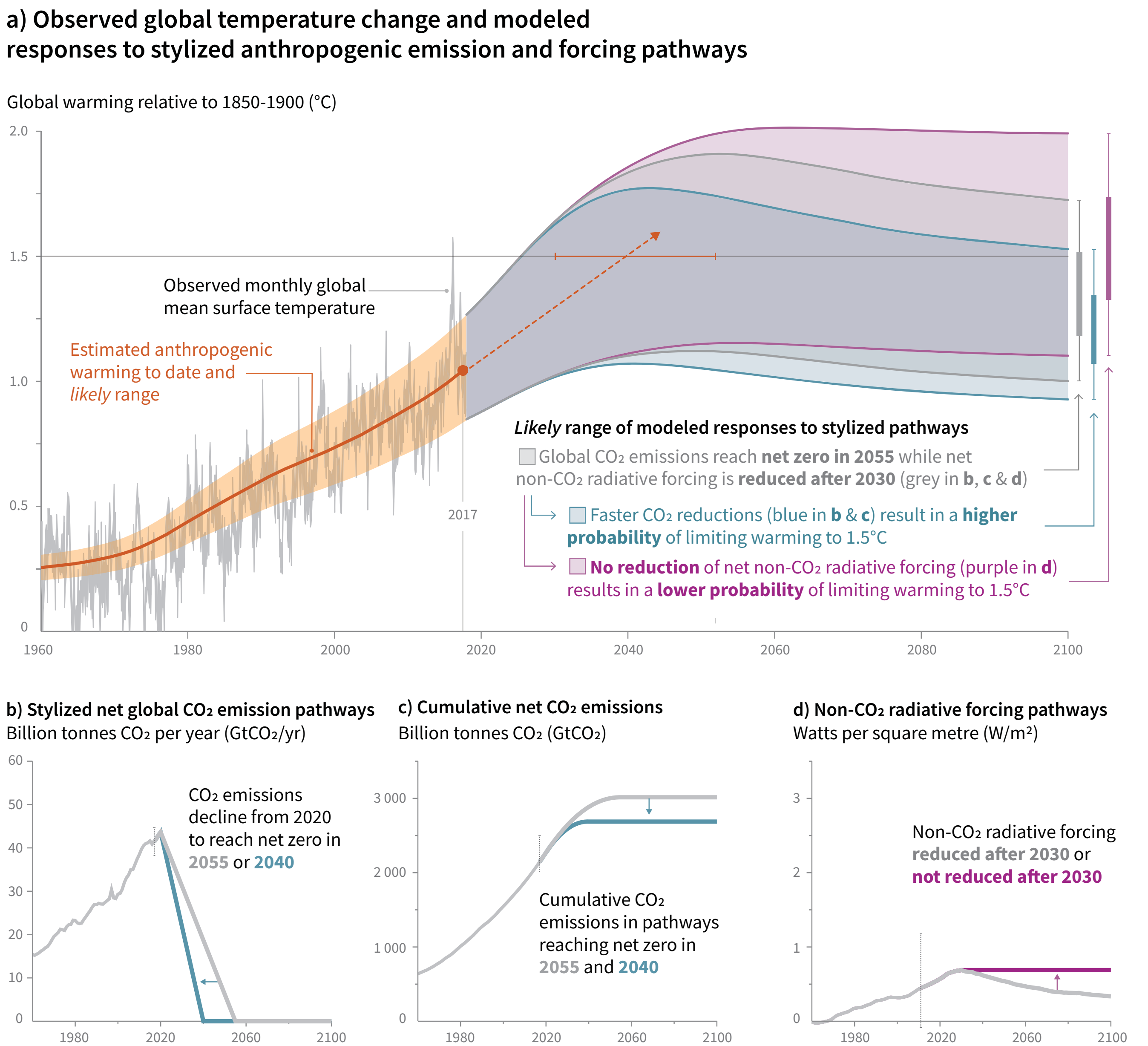
[4] SPM BOX.1: Core Concepts

[5] Present level of global warming is defined as the average of a 30-year period centered on 2017 assuming the recent rate of warming continues.

[6] This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {1.2.1, Table 1.1}

A2.2. Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer timescales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and reverse ocean acidification (*medium confidence*) and will be required to minimise sea level rise (*high confidence*). {Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2}

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C



Faster immediate CO_2 emission reductions limit cumulative CO_2 emissions shown in panel **(c)**.

Maximum temperature rise is determined by cumulative net CO_2 emissions and net non-CO_2 radiative forcing due to methane, nitrous oxide, aerosols and other anthropogenic forcing agents.

Figure SPM.1: Panel a: Observed monthly global mean surface temperature (GMST) change grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively central estimate and *likely* range of the time at which 1.5°C is reached if the current rate of warming continues. The grey plume on the right of Panel a) shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd – 66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {1.2.1, 1.2.3, 1.2.4, 2.3, Chapter 1 Figure 1.2 & Chapter 1 Supplementary Material, Cross-Chapter Box 2}

A3. Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*) (Figure SPM.2). {1.3, 3.3, 3.4, 5.6}

A3.1. Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). {1.4, 3.4, 3.5, Figure SPM.2}

A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8}

A3.3. Adaptation and mitigation are already occurring (*high confidence*). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multi-level and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3}

B. Projected Climate Change, Potential Impacts and Associated Risks

B1. Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5°C,[8] and between 1.5°C and 2°C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {3.3}

B1.1. Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5°C supports the assessment that an additional 0.5°C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

B1.2. Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about

[7] Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

[8] Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3}

B1.3. Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence*). Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2.0°C than at 1.5°C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (*medium confidence*). {3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6}

B2. By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depends on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {3.3, 3.4, 3.6 }

B2.1. Model-based projections of global mean sea level rise (relative to 1986-2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5°C global warming, 0.1 m (0.04-0.16 m) less than for a global warming of 2°C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to 10 million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {3.4.4, 3.4.5, 4.3.2}

B2.2. Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered around 1.5°C to 2°C of global warming (*medium confidence*). {3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3, Figure SPM.2}

B2.3. Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems, and infrastructure reinforcement (*medium confidence*). {3.4.5, Figure SPM.2, Box 3.5}

B3. On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater, and coastal ecosystems and to retain more of their services to humans (*high confidence*). (Figure SPM.2) {3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3}

B3.1. Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires, and the spread of invasive species, are lower at 1.5°C compared to 2°C of global warming (*high confidence*). {3.4.3, 3.5.2}

B3.2. Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, compared with 13% (interquartile range 8–20%) at 2°C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (*medium confidence*). {3.4.3.1, 3.4.3.5}

B3.3. High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and will proceed with further warming. Limiting global warming to 1.5°C rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {3.3.2, 3.4.3, 3.5.5}

B4. Limiting global warming to 1.5°C compared to 2ºC is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm water coral reef ecosystems (*high confidence*). {3.3, 3.4, 3.5, Boxes 3.4, 3.5}

B4.1. There is *high confidence* that the probability of a sea-ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {3.3.8, 3.4.4.7}

B4.2. Global warming of 1.5°C is projected to shift the ranges of many marine species, to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources, and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2ºC (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*). {3.4.4, Box 3.4}

B4.3. The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C,

[9] Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, e.g., from algae to fish (*high confidence*). {3.3.10, 3.4.4}

B4.4. Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (*medium confidence)* but are projected to be less at 1.5ºC of global warming than at 2ºC. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (*medium confidence*). {3.4.4, Box 3.4}

B5. Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. (Figure SPM.2) {3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2}

B5.1. Populations at disproportionately higher risk of adverse consequences of global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small-island developing states, and least developed countries (*high confidence)*. Poverty and disadvantages are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3}

B5.2. Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence)*. Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). {3.4.7, 3.4.8, 3.5.5.8}

B5.3. Limiting warming to 1.5°C, compared with 2ºC, is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO_2 dependent, nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2ºC than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4}

B5.4. Depending on future socioeconomic conditions, limiting global warming to 1.5°C, compared to 2°C, may reduce the proportion of the world population exposed to a climate-change induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states would experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5°C, as compared to 2°C (*medium confidence*). {3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

B5.5. Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century[10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2 °C (*medium confidence*). {3.5.2, 3.5.3}

B5.6. Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}

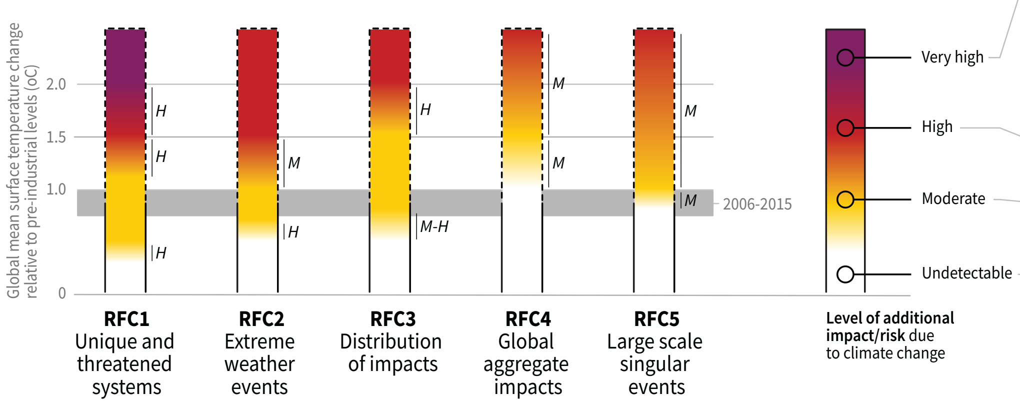
B5.7. There are multiple lines of evidence that since the AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1.0°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). (Figure SPM.2) {3.4.13; 3.5, 3.5.2}

[10] Here, impacts on economic growth refer to changes in GDP. Many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize.

How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

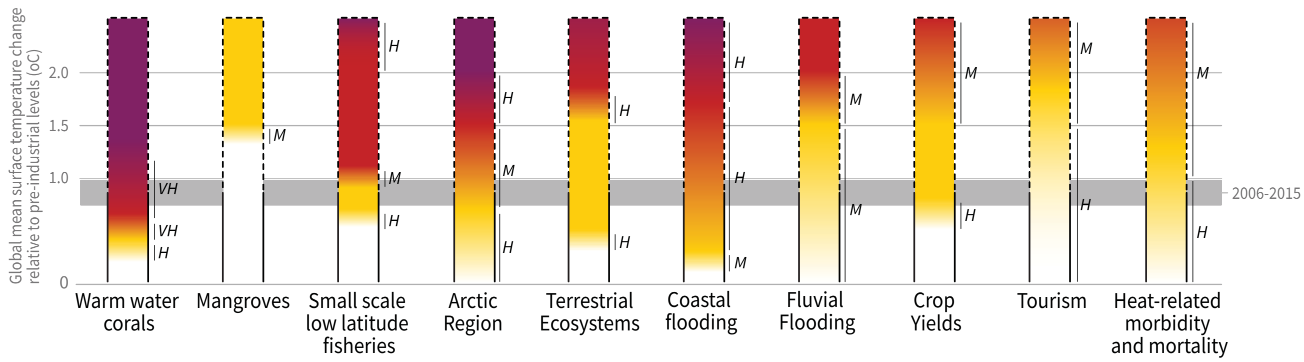
Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)



Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
Red indicates severe and widespread impacts/risks.
Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
White indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Figure SPM.2: Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies, and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in the AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. **RFC1 Unique and threatened systems:** ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers, and biodiversity hotspots. **RFC2 Extreme weather events**: risks/impacts to human health, livelihoods, assets, and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding. **RFC3 Distribution of impacts:** risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. **RFC4 Global aggregate impacts:** global monetary damage, global scale degradation and loss of ecosystems and biodiversity. **RFC5 Large-scale singular events:** are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets. {3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1 5.5.3, 5.6.1, Box 3.4}

B6. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*). {Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5}

B6.1. A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (e.g., ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (e.g., coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (e.g., efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, community-based adaptation) and urban areas (e.g., green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4}.

B6.2. Adaptation is expected to be more challenging for ecosystems, food and health systems at 2°C of global warming than for 1.5°C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5°C (*high confidence*). {3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3}

B6.3. Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems, and human health (*medium confidence*) {Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5}

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C1. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C[11] CO_2 emissions are projected to decline by about 20% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2075 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (*high confidence*) (Figure SPM.3a) {2.1, 2.3, Table 2.4}

C1.1. CO_2 emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges, and potential synergies and trade-offs with sustainable development. (*high confidence*). (Figure SPM.3b) {2.3.2, 2.3.4, 2.4, 2.5.3}

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[11] References to pathways limiting global warming to 2ºC are based on a 66% probability of staying below 2ºC.

C1.2. Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for two to three decades. Non-CO_2 emissions[12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5°C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5°C model pathways. (*high confidence*) (Figure SPM.3a) {2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2}

C1.3. Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the preindustrial period, i.e. staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the preindustrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5°C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material}

C1.4. Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps as well as substantial risks,

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[12] Non-CO_2 emissions included in this report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {x.y}

[13] There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5°C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this report.

[14] Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {x.y}

[15] These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*). {4.3.8, Cross-Chapter Box 10 in Chapter 4}

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM3B.

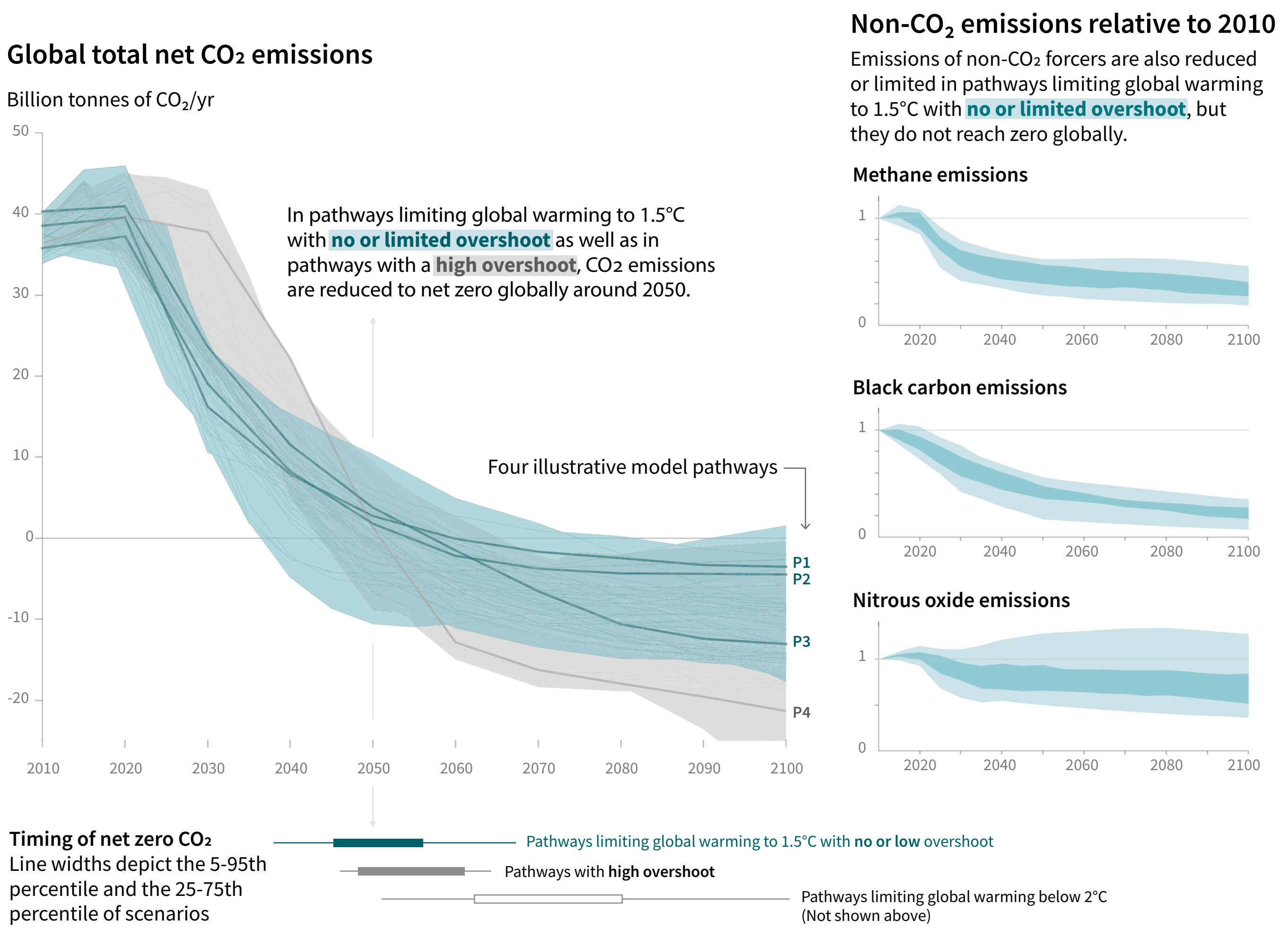
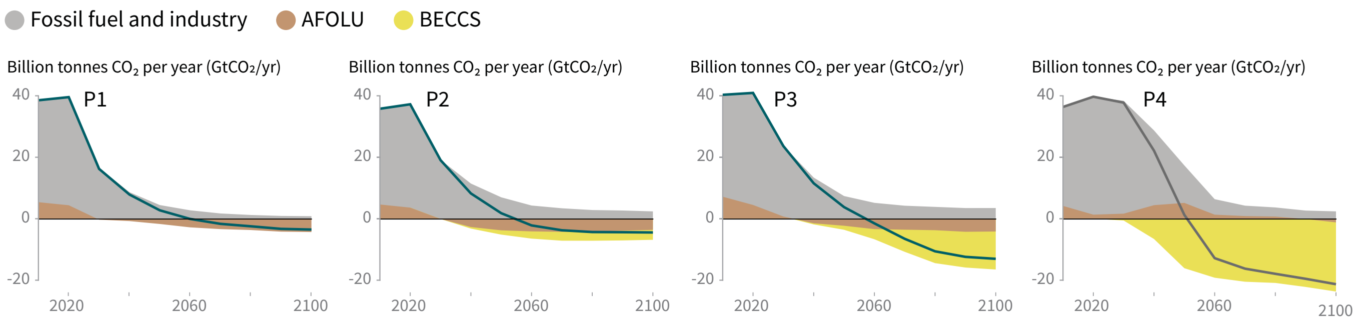


Figure SPM.3a: Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limit global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for the emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business, and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A down-sized energy system enables rapid decarbonisation of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or low overshoot	No or low overshoot	No or low overshoot	High overshoot	No or low overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-59,-40)
└ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-104,-91)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-55,-38)
└ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12, 7)
└ in 2050 (% rel to 2010)	-32	2	21	44	(-11, 22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47, 65)
└ in 2050 (%)	77	81	63	70	(69, 87)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
└ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
└ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
└ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
└ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
└ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(243,438)
└ in 2050 (% rel to 2010)	832	1327	878	1137	(575,1300)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550, 1017)
└ of which BECCS ($GtCO_2$)	0	151	414	1191	(364, 662)
Land area of bioenergy crops in 2050 (million hectare)	22	93	283	724	(151, 320)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-46,-23)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,4)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on SAR GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b: Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socioeconomic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry, agriculture, forestry and other land use (AFOLU), and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4, correspond to the LED, S1, S2, and S5 pathways assessed in Chapter 2. (Figure SPM.3a) {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C2. Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5}

C2.1. Pathways that limit global warming to 1.5°C with no or limited overshoot show system changes that are more rapid and pronounced over the next two decades than in 2°C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5°C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4}

C2.2. In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5°C with no or limited overshoot (for more details see Figure SPM.3b), generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C (*high confidence*). In 1.5°C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2°C pathways, particularly before 2050 (*high confidence*). In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2%) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation (Figure SPM.3b) {2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2}

C2.3. CO_2 emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 75–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (*high confidence*). {2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2}

C2.4. The urban and infrastructure system transition consistent with limiting global warming to 1.5°C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2°C (see 2.4.3; 4.3.3; 4.2.1) (*medium confidence*). Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2}.

C2.5. Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5°C with no or limited overshoot project the conversion of 0.5–8 million km^2 of pasture and 0–5 million km^2 of non-pasture agricultural land for food and feed crops into 1–7 million km^2 for energy crops and a 1 million km^2 reduction to 10 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {2.4.4, Figure 2.24, 4.3.2, 4.5.2, Cross-Chapter Box 7 in Chapter 3}

C2.6 Total annual average energy-related mitigation investment for the period 2015 to 2050 in pathways limiting warming to 1.5°C is estimated to be around 900 billion USD2015 (range of 180 billion to 1800 billion USD2015 across six models[17]). This corresponds to total annual average energy supply investments of 1600 to 3800 billion USD2015 and total annual average energy demand investments of 700 to 1000 billion USD2015 for the period 2015 to 2050, and an increase in total energy-related investments of about 12% (range of 3% to 23%) in 1.5°C pathways relative to 2°C pathways. Average annual investment in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of five (range of factor of 4 to 5) by 2050 compared to 2015 (*medium confidence*). {2.5.2, Box 4.8, Figure 2.27}

C2.7. Modelled pathways limiting global warming to 1.5°C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3-4 times higher than in pathways limiting global warming to below 2°C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5°C mitigation pathways is limited and was not assessed in this report. Knowledge gaps remain in the integrated assessment of the economy wide costs and benefits of mitigation in line with pathways limiting warming to 1.5°C. {2.5.2; 2.6; Figure 2.26}

[16] The projected land use changes presented are not deployed to their upper limits simultaneously in a single pathway.

[17] Including two pathways limiting warming to 1.5°C with no or limited overshoot and four pathways with high overshoot.

C3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {2.3, 2.4, 3.6.2, 4.3, 5.4}

C3.1. Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (*high confidence*). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {2.3.4, 3.6.2, 4.3.2, 4.3.7}

C3.2. In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2\ yr^{-1}$ in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2\ yr^{-1}$ and afforestation potential of up to 3.6 $GtCO_2\ yr^{-1}$ assessed based on recent literature (*medium confidence*). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (*high confidence*). (Figure SPM.3b) {2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4}

C3.3. Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b). (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11}

C3.4. Most current and potential CDR measures could have significant impacts on land, energy, water, or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (Figure SPM.3b). {2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3}

C3.5. Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (*medium confidence*). (Figure SPM.4) {2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4}

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D1. Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] in 2030 of 52–58 $GtCO_2eq\ yr^{-1}$ (*medium confidence)*. Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO_2 emissions start to decline well before 2030 (*high confidence*). {1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4}

D1.1. Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq\ yr^{-1}$ in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq\ yr^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards (*medium confidence*). {2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2}

D1.2. Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4}

D1.3. The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long-term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {2.3.5, 4.4.5, 5.4.2}

D2. The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1}

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[18] GHG emissions have been aggregated with 100-year GWP values as introduced in the IPCC Second Assessment Report

D2.1. Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5°C or 2°C and development goals that include poverty eradication, reducing inequalities, and climate action (*high confidence*) {Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1}

D2.2. The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5}

D2.3. Mitigation and adaptation consistent with limiting global warming to 1.5°C are underpinned by enabling conditions, assessed in SR1.5 across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional dimensions of feasibility. Strengthened multi-level governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C consistent systems transitions. *(high confidence*) {1.4, Cross-Chapter Box 3 in Chapter 1, 4.4, 4.5, 5.6}

D3. Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*). {1.4, 4.3, 4.5}

D3.1. Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5°C of global warming (*high confidence*). {1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2}

D3.2. Adaptation to 1.5°C global warming can also result in trade–offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3}

D3.3. A mix of adaptation and mitigation options to limit global warming to 1.5°C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*) {4.3.2, 4.3.3, 4.4.1, 4.4.2}

D3.4. Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5°C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

D4. Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. *(high confidence*) (Figure SPM.4) {2.5, 4.5, 5.4}

D4.1. 1.5°C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production), and 14 (oceans) (*very high confidence*). Some 1.5°C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), 6 (water), and 7 (energy access), if not carefully managed (*high confidence*) (Figure SPM.4). {5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3}

D4.2. 1.5°C pathways that include low energy demand (e.g., see P1 in Figure SPM.3a and SPM.3b), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5◦C. (*high confidence*) (Figure SPM.3b, Figure SPM.4) {2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4}

D4.3. 1.5°C and 2°C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). {Figure SPM.4, 5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

D4.4. Mitigation consistent with 1.5°C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {5.4.1.2, Box 5.2}

D4.5. Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5°C pathways. (*high confidence*) {2.4.3, 5.4.2, Figure 5.5}

Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

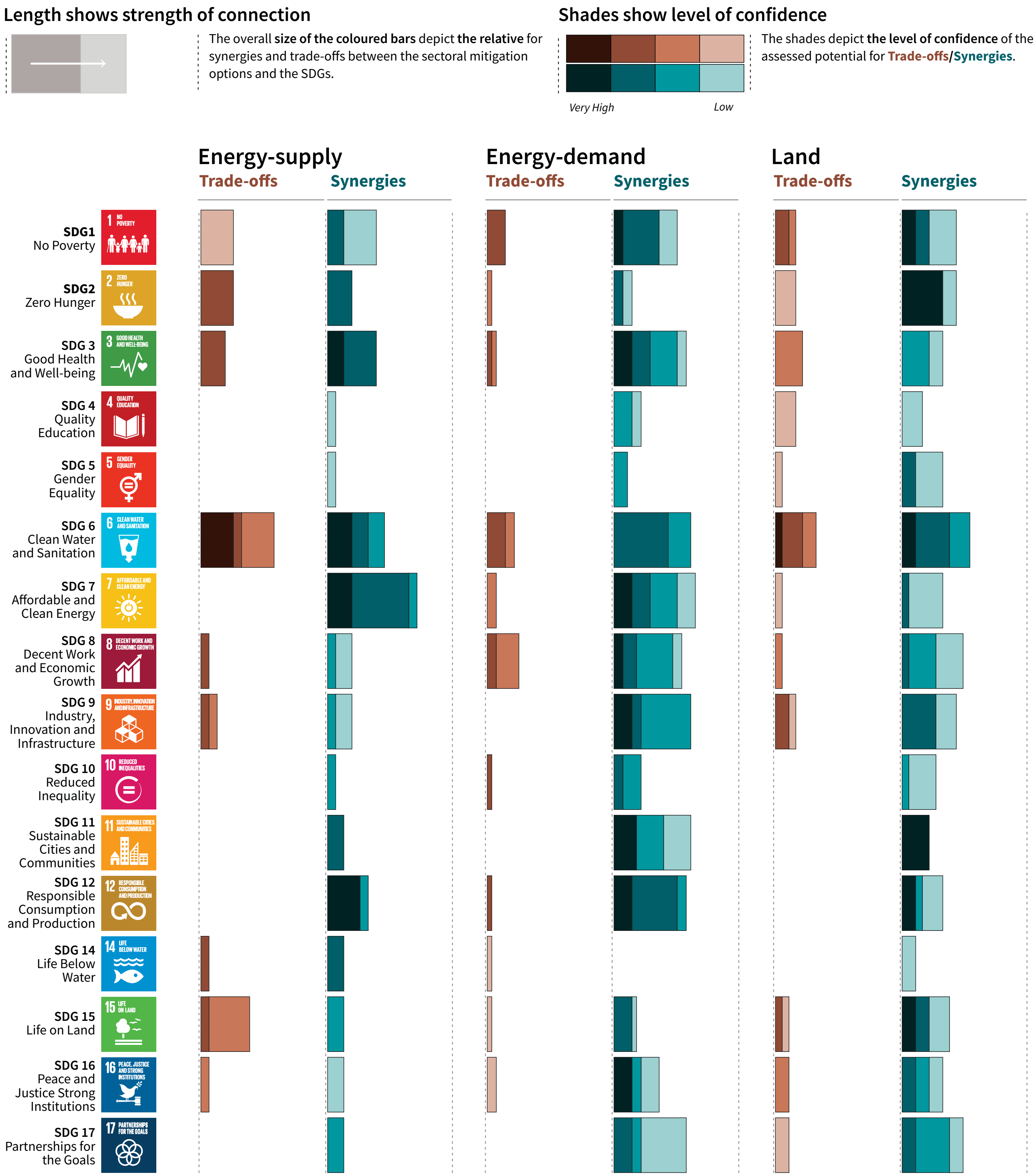

Figure SPM.4: Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5ºC. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in Table 5.2. For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see Table 5.2) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have *low confidence* due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, CCS with bio-energy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets & reduced food waste, soil sequestration, livestock & manure management, reduced deforestation, afforestation & reforestation, responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {5.4, Table 5.2, Figure 5.2}

Statement for knowledge gap:
Information about the net impacts of mitigation on sustainable development in 1.5°C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5°C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in Figure SPM.4 is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D5. Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6}

D5.1. Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges including access to finance and mobilisation of funds (*high confidence*) {2.5.2, 4.4.5}

D5.2. Adaptation finance consistent with global warming of 1.5°C is difficult to quantify and compare with 2°C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments, from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5°C than for 2°C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and UNFCCC channels (*medium confidence*). More recently there is a growing understanding of the scale and increase in NGO and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*). {4.4.5, 4.6}

D5.3. Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion USD2010 between 2016 and 2035 representing about 2.5% of the world GDP (*medium confidence*). {2.5.2, 4.4.5, Box 4.8}

D5.4. Policy tools can help mobilise incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*) {1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3 and 11 in Chapter 4, 4.4.5, 5.5.2}

D5.5. The systems transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {4.4.4, 4.4.5}.

D5.6. Education, information, and community approaches, including those that are informed by Indigenous knowledge and local knowledge, can accelerate the wide scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities, and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5°C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5}

D6. Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities *(high confidence)*. {Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3}

D6.1. Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5}

D6.2. The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {5.5.1, 5.5.3, Figure 5.1}

D6.3. Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5°C. (*high confidence*) {2.3.1, 2.5.3, 5.5.2}

D7. Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5}

D7.1. Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5°C (*very high confidence*). {1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3}.

D7.2. Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing and cooperation on technology development and transfer can ensure participation, transparency, capacity building, and learning among different players (*high confidence*). {2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 4.4.5, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3}

D7.3. International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5°C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {2.3.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7}.

D7.4. Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5ºC, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {1.4.2, 2.3.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3}

Box SPM 1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {1.2.1.1}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {1.2.1.2}

Global warming: The estimated increase in GMST averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {1.2.1}

Net zero CO_2 emissions: Net-zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the preindustrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this Summary for Policymakers, the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C are classified as 'no overshoot'; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 are classified as '1.5°C limited-overshoot'; while those exceeding 1.6°C but still returning to 1.5°C by 2100 are classified as 'higher-overshoot'.

[19] Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation, and climate resilience.

Chapter 1: Framing and Context

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Table of Content

Executive Summary

This chapter frames the context, knowledge-base and assessment approaches used to understand the impacts of 1.5°C global warming above pre-industrial levels and related global greenhouse gas emission pathways, building on the IPCC Fifth Assessment Report (AR5), in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

Human-induced warming reached approximately 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017, increasing at 0.2°C (±0.1°C) per decade (*high confidence*). Global warming is defined in this report as an increase in combined surface air and sea surface temperatures averaged over the globe and a 30-year period. Unless otherwise specified, warming is expressed relative to the period 1850-1900, used as an approximation of pre-industrial temperatures in AR5. For periods shorter than 30 years, warming refers to the estimated average temperature over the 30 years centered on that shorter period, accounting for the impact of any temperature fluctuations or trend within those 30 years. Accordingly, warming up to the decade 2006-2015 is assessed at 0.87°C (±0.12°C *likely* range). Since 2000, the estimated level of human-induced warming has been equal to the level of observed warming with a *likely* range of ±20% accounting for uncertainty due to contributions from solar and volcanic activity over the historical period (*high confidence*). {1.2.1}

Warming greater than the global average has already been experienced in many regions and seasons, with average warming over land higher than over the ocean (*high confidence*). Most land regions are experiencing greater warming than the global average, while most ocean regions are warming at a slower rate. Depending on the temperature dataset considered, 20-40% of the global human population live in regions that, by the decade 2006-2015, had already experienced warming of more than 1.5°C above pre-industrial in at least one season (*medium confidence*). {1.2.1 & 1.2.2}

Past emissions alone are *unlikely* to raise global-mean temperature to 1.5°C above pre-industrial levels but past emissions do commit to other changes, such as further sea level rise (*high confidence*)**.** If all anthropogenic emissions (including aerosol-related) were reduced to zero immediately, any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the next two to three decades (*high confidence*), and *likely* less than 0.5°C on a century timescale (*medium confidence*), due to the opposing effects of different climate processes and drivers. A warming greater than 1.5°C is therefore not geophysically unavoidable: whether it will occur depends on future rates of emission reductions. {1.2.3, 1.2.4}

1.5°C-consistent emission pathways are defined as those that, given current knowledge of the climate response, provide a one-in-two to two-in-three chance of warming either remaining below 1.5°C, or returning to 1.5°C by around 2100 following an overshoot. Overshoot pathways are characterized by the peak magnitude of the overshoot, which may have implications for impacts. All 1.5°C-consistent pathways involve limiting cumulative emissions of long-lived greenhouse gases, including carbon dioxide and nitrous oxide, and substantial reductions in other climate forcers (*high confidence*). Limiting cumulative emissions requires either reducing net global emissions of long-lived greenhouse gases to zero before the cumulative limit is reached, or net negative global emissions (anthropogenic removals) after the limit is exceeded. {1.2.3, 1.2.4, Cross-Chapter Boxes 1 and 2}

This report assesses projected impacts at a global average warming of 1.5°C and higher levels of warming. Global warming of 1.5°C is associated with global average surface temperatures fluctuating naturally on either side of 1.5°C, together with warming substantially greater than 1.5°C in many regions and seasons (*high confidence*), all of which must be taken into account in the assessment of impacts. Impacts at 1.5°C of warming also depend on the emission pathway to 1.5°C. Very different impacts result from pathways that remain below 1.5°C versus pathways that return to

1.5°C after a substantial overshoot, and when temperatures stabilize at 1.5°C versus a transient warming past 1.5°C. (*medium confidence*) {1.2.3, 1.3}

Ethical considerations, and the principle of equity in particular, are central to this report, recognising that many of the impacts of warming up to and beyond 1.5°C, and some potential impacts of mitigation actions required to limit warming to 1.5°C, fall disproportionately on the poor and vulnerable (*high confidence*). Equity has procedural and distributive dimensions and requires fairness in burden sharing, between generations, and between and within nations. In framing the objective of holding the increase in the global average temperature rise to well below 2°C above pre-industrial levels, and to pursue efforts to limit warming to 1.5°C, the Paris Agreement associates the principle of equity with the broader goals of poverty eradication and sustainable development, recognising that effective responses to climate change require a global collective effort that may be guided by the 2015 United Nations Sustainable Development Goals. {1.1.1}

Climate adaptation refers to the actions taken to manage impacts of climate change by reducing vulnerability and exposure to its harmful effects and exploiting any potential benefits. Adaptation takes place at international, national and local levels. Subnational jurisdictions and entities, including urban and rural municipalities, are key to developing and reinforcing measures for reducing weather- and climate-related risks. Adaptation implementation faces several barriers including unavailability of up-to-date and locally-relevant information, lack of finance and technology, social values and attitudes, and institutional constraints (*high confidence*). Adaptation is more likely to contribute to sustainable development when polices align with mitigation and poverty eradication goals (*medium confidence*) {1.1, 1.4}

Ambitious mitigation actions are indispensable to limit warming to 1.5°C while achieving sustainable development and poverty eradication (*high confidence*). Ill-designed responses, however, could pose challenges especially—but not exclusively—for countries and regions contending with poverty and those requiring significant transformation of their energy systems. This report focuses on 'climate-resilient development pathways' , which aim to meet the goals of sustainable development, including climate adaptation and mitigation, poverty eradication and reducing inequalities. But any feasible pathway that remains within 1.5°C involves synergies and trade-offs (*high confidence*). Significant uncertainty remains as to which pathways are more consistent with the principle of equity. {1.1.1, 1.4}

Multiple forms of knowledge, including scientific evidence, narrative scenarios and prospective pathways, inform the understanding of 1.5°C. This report is informed by traditional evidence of the physical climate system and associated impacts and vulnerabilities of climate change, together with knowledge drawn from the perceptions of risk and the experiences of climate impacts and governance systems. Scenarios and pathways are used to explore conditions enabling goal-oriented futures while recognizing the significance of ethical considerations, the principle of equity, and the societal transformation needed. {1.2.3, 1.5.2}

There is no single answer to the question of whether it is feasible to limit warming to 1.5°C and adapt to the consequences. Feasibility is considered in this report as the capacity of a system as a whole to achieve a specific outcome. The global transformation that would be needed to limit warming to 1.5°C requires enabling conditions that reflect the links, synergies and trade-offs between mitigation, adaptation and sustainable development. These enabling conditions have many systemic dimensions—geophysical, environmental-ecological, technological, economic, socio-cultural and institutional—that may be considered through the unifying lens of the Anthropocene, acknowledging profound, differential but increasingly geologically significant human influences on the Earth system as a whole. This framing also emphasises the global interconnectivity of past, present and future human–environment relations, highlighing the need and opportunities for integrated responses to achieve the goals of the Paris Agreement. {1.1, Cross-Chapter Box 1}

1.1 Assessing the knowledge base for a 1.5°C warmer world

Human influence on climate has been the dominant cause of observed warming since the mid-20th century, while global average surface temperature warmed by 0.85°C between 1880 and 2012, as reported in the IPCC Fifth Assessment Report, or AR5 (IPCC, 2013b). Many regions of the world have already experienced greater regional-scale warming, with 20-40% of the global population (depending on the temperature dataset used) having experienced over 1.5°C of warming in at least one season (Figure 1.1 and Chapter 3 Section 3.3). Temperature rise to date has already resulted in profound alterations to human and natural systems, bringing increases in some types of extreme weather, droughts, floods, sea level rise and biodiversity loss, and causing unprecedented risks to vulnerable persons and populations (IPCC, 2012a, 2014b; Mysiak et al., 2016), Chapter 3 Section 3.4). The most affected people live in low and middle income countries, some of which have already experienced a decline in food security, linked in turn to rising migration and poverty (IPCC, 2012a). Small islands, megacities, coastal regions and high mountain ranges are likewise among the most affected (Albert et al., 2017). Worldwide, numerous ecosystems are at risk of severe impacts, particularly warm-water tropical reefs and Arctic ecosystems (IPCC, 2014d).

This report assesses current knowledge of the environmental, technical, economic, financial, socio-cultural, and institutional dimensions of a 1.5°C warmer world (meaning, unless otherwise specified, a world in which warming has been limited to 1.5°C relative to pre-industrial levels). Differences in vulnerability and exposure arise from numerous non-climatic factors (IPCC, 2014b). Global economic growth has been accompanied by increased life expectancy and income in much of the world - but in addition to environmental degradation and pollution, many regions remain characterised by significant poverty, severe inequity in income distribution and access to resources, amplifying vulnerability to climate change (Dryzek, 2016; Pattberg and Zelli, 2016; Bäckstrand et al., 2017; Lövbrand et al., 2017). World population continues to rise, notably in hazard-prone small and medium-sized cities in low- and moderate-income countries (Birkmann et al., 2016). The spread of fossil-fuel-based material consumption and changing lifestyles is a major driver of global resource use, and the main contributor to rising greenhouse gas (GHG) emissions (Fleurbaey et al., 2014).

The overarching context of this report is this: human influence has become a principal agent of change on the planet, shifting the world out of the relatively stable Holocene period into a new geological era, often termed the Anthropocene (Box 1.1). Responding to climate change in the Anthropocene will require approaches that integrate multiple levels of inter-connectivity across the global community.

This chapter is composed of seven sections linked to the remaining four chapters of the report. The introductory section 1.1 situates the basic elements of the assessment within the context of sustainable development, considerations of ethics, equity and human rights, and their link to poverty. Section 1.2 focuses on understanding 1.5°C, global versus regional warming, 1.5°C–consistent pathways and associated emissions. Section 1.3 frames the impacts at 1.5°C and beyond on natural and human systems. The section on strengthening the global response (1.4) frames different responses, governance and implementation, and trade-offs and synergies between mitigation, adaptation and the Sustainable Development Goals (SDGs) under transformation, transformation pathways, and transition. Section 1.5 provides assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development. Section 1.6 defines approaches used to communicate confidence, uncertainty and risk, while 1.7 presents the storyline of the whole report.

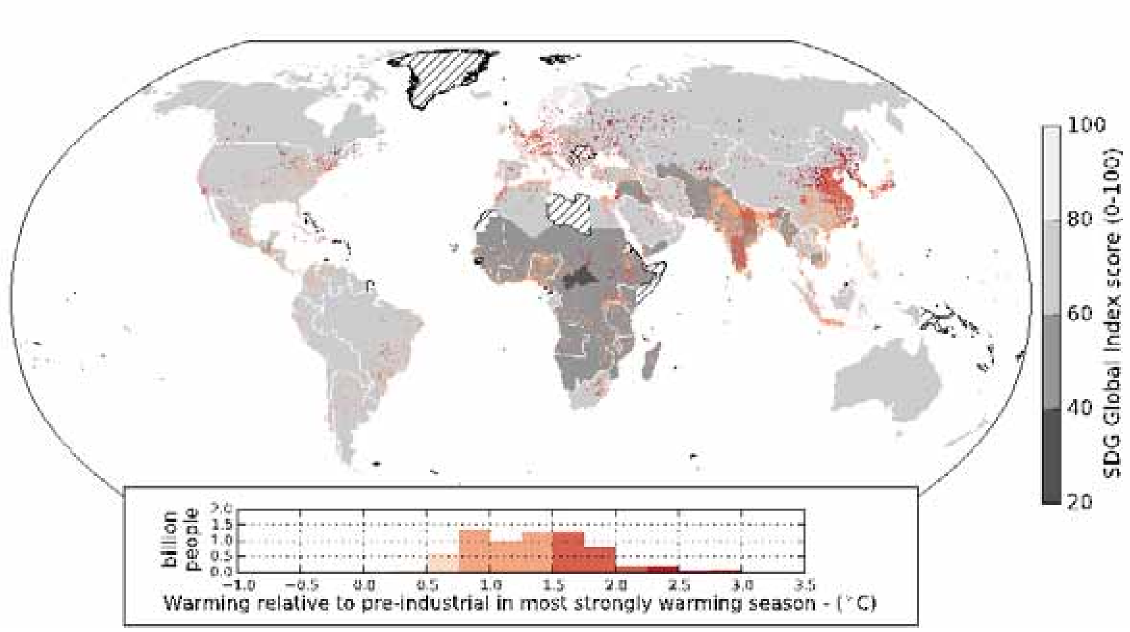

Figure 1.1: **Human experience of present–day warming.** Colours indicated by the inset histogram show estimated warming for the season that has warmed the most at a given location between the periods 1850-1900 and 2006–2015, during which global average temperatures rose by 0.91°C in this dataset (Cowtan and Way, 2014), and 0.87°C in the multi-dataset average (Table 1.1 and Figure 1.3). The density of dots indicates the population (in 2010) in any 1°x1° grid box. The underlay shows national SDG Global Index Scores indicating performance across the 17 Sustainable Development Goals. Hatching indicates missing SDG index data (e.g., Greenland). The histogram shows the number of people of the 2010 global population living in regions experiencing different levels of warming (at 0.25°C increments). See Technical Annex 1.A for further details.

Box 1.1: The Anthropocene: Strengthening the global response to 1.5°C global warming

Introduction

The concept of the Anthropocene can be linked to the aspiration of the Paris Agreement. The abundant empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System (Steffen et al., 2016; Waters et al., 2016) has led many scientists to call for an acknowledgement that the Earth has entered a new geological epoch: the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002; Gradstein et al., 2012). Although rates of change in the Anthropocene are necessarily assessed over much shorter periods than those used to calculate long-term baseline rates of change, and therefore present challenges for direct comparison, they are nevertheless striking. The rise in global CO_2 concentration since 2000 is about 20 ppm/decade, which is up to 10 times faster than any sustained rise in CO_2 during the past 800,000 years (Lüthi et al., 2008; Bereiter et al., 2015). AR5 found that the last geological epoch with similar atmospheric CO_2 concentration was the Pliocene, 3.3 to 3.0 Ma (Masson-Delmotte et al., 2013). Since 1970 the global average temperature has been rising at a rate of 1.7°C per century, compared to a long-term decline over the past 7,000 years at a baseline rate of 0.01°C per century (NOAA 2016, Marcott et al. 2013). These global-level rates of human-driven change far exceed the rates of change driven by geophysical or biosphere forces that have altered the Earth System trajectory in the past (e.g., Summerhayes 2015; Foster et al. 2017); even abrupt geophysical events do not approach current rates of human-driven change.

The geological dimension of the Anthropocene and 1.5°C global warming
The process of formalising the Anthropocene is on-going (Zalasiewicz et al., 2017), but a strong majority of the Anthropocene Working Group (AWG) established by the Sub–Committee on Quaternary Stratigraphy of the International Commission on Stratigraphy have agreed that: (i) the Anthropocene has a geological merit; (ii) it should follow the Holocene as a formal epoch in the Geological Time Scale; and, that (iii) its onset should be defined as the mid–20th century. Potential markers in the stratigraphic record include an array of novel manufactured materials of human origin, and "these combined signals render the Anthropocene stratigraphically distinct from the Holocene and earlier epochs" (Waters et al., 2016). The Holocene period, which itself was formally adopted in 1885 by geological science community, began 11,700 years ago with a more stable warm climate providing for emergence of human civilisation and growing human-nature interactions that have expanded to give rise to the Anthropocene (Waters et al., 2016).

The Anthropocene and the Challenge of a 1.5° C warmer world
The Anthropocene can be employed as a "boundary concept" (Brondizio et al., 2016) that frames critical insights into understanding the drivers, dynamics and specific challenges in responding to the ambition of keeping global temperature well below 2°C while pursuing efforts towards and adapting to a 1.5°C warmer world. The UNFCCC and its Paris Accord recognize the ability of humans to influence geophysical planetary processes (Chapter 2, Cross-Chapter Box 1 in this Chapter). The Anthropocene offers a structured understanding of the culmination of past and present human–environmental relations and provides an opportunity to better visualize the future to minimize pitfalls (Pattberg and Zelli, 2016; Delanty and Mota, 2017), while acknowledging the differentiated responsibility and opportunity to limit global warming and invest in prospects for climate-resilient sustainable development (Harrington, 2016) (Chapter 5). The Anthropocene also provides an opportunity to raise questions regarding the regional differences, social inequities and uneven capacities and drivers of global social–environmental changes, which in turn inform the search for solutions as explored in Chapter 4 of this report (Biermann et al., 2016). It links uneven influences of human actions on planetary functions to an uneven distribution of impacts (assessed in Chapter 3) as well as the responsibility and response capacity to for example, limiting global warming to no more than a 1.5°C rise above pre–industrial levels. Efforts to curtail greenhouse gas emissions without incorporating the intrinsic interconnectivity and disparities associated with the Anthropocene world may themselves negatively affect the development ambitions of some regions more than others and negate sustainable development efforts (see Chapter 2 and Chapter 5).

1.1.1 Equity and a 1.5°C warmer world

The AR5 suggested that equity, sustainable development, and poverty eradication are best understood as mutually supportive and co-achievable within the context of climate action, and are underpinned by various other international hard and soft law instruments (Denton et al., 2014; Fleurbaey et al., 2014; Klein et al., 2014; Olsson et al., 2014; Porter et al., 2014; Stavins et al., 2014). The aim of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) to 'pursue efforts to limit' the rise in global temperatures to 1.5°C above pre-industrial levels raises ethical concerns that have long been central to climate debates (Fleurbaey et al., 2014; Kolstad et al., 2014). The Paris Agreement makes particular reference to the principle of equity, within the context of broader international goals of sustainable development and poverty eradication. Equity is a long-standing principle within international law and climate change law in particular (Dinah, 2008; Bodansky et al., 2017).

The AR5 describes equity as having three dimensions: intergenerational (fairness between generations), international (fairness between states), and national (fairness between individuals) (Fleurbaey et al., 2014). The principle is generally agreed to involve both procedural justice (i.e.

participation in decision making) and distributive justice (i.e. how the costs and benefits of climate actions are distributed) (Kolstad et al., 2014; Savaresi, 2016; Reckien et al., 2017). Concerns regarding equity have frequently been central to debates around mitigation, adaptation and climate governance (Caney, 2005; Schroeder et al., 2012; Ajibade, 2016; Reckien et al., 2017; Shue, 2018). Hence, equity provides a framework for understanding the asymmetries between the distributions of benefits and costs relevant to climate action (Schleussner et al., 2016; Aaheim et al., 2017).

Four key framing asymmetries associated with the conditions of 1.5°C warmer world have been noted (Okereke, 2010; Harlan et al., 2015; Ajibade, 2016; Savaresi, 2016; Reckien et al., 2017) and are reflected in the report's assessment. The first concerns differential contributions to the problem: the observation that the benefits from industrialization have been unevenly distributed and those who benefited most historically also have contributed most to the current climate problem and so bear greater responsibility (Shue, 2013; Otto et al., 2017; Skeie et al., 2017). The second asymmetry concerns differential impact: the worst impacts tend to fall on those least responsible for the problem, within states, between states, and between generations (Fleurbaey et al., 2014; Shue, 2014; Ionesco et al., 2016). The third is the asymmetry in capacity to shape solutions and response strategies, such that the worst-affected states, groups and individuals are not always well-represented (Robinson and Shine, 2018). Fourth, there is an asymmetry in future response capacity: some states, groups and places are at risk of being left behind as the world progresses to a low-carbon economy (Fleurbaey et al., 2014; Shue, 2014; Humphreys, 2017).

A sizeable and growing literature exists on how best to operationalize climate equity considerations, drawing on other concepts mentioned in the Paris Agreement, notably its explicit reference to human rights (OHCHR, 2009; Caney, 2010; Adger et al., 2014; Fleurbaey et al., 2014; IBA, 2014; Knox, 2015; Duyck et al., 2018; Robinson and Shine, 2018). Human rights comprise internationally agreed norms that align with the Paris ambitions of poverty eradication, sustainable development and the reduction of vulnerability (Caney, 2010; Fleurbaey et al., 2014; OHCHR, 2015). In addition to defining substantive rights (such as to life, health and shelter) and procedural rights (such as to information and participation), human rights instruments prioritise the rights of marginalised, children, vulnerable and indigenous persons, and those discriminated against on grounds such as gender, race, age or disability (OHCHR, 2017). Several international human rights obligations that are relevant to the implementation of climate actions and consonant with UNFCCC undertakings in the areas of mitigation, adaptation, finance, and technology transfer (Knox, 2015; OHCHR, 2015; Humphreys, 2017).

Much of this literature is still new and evolving (Holz et al., 2017; Dooley et al., 2018; Klinsky and Winkler, 2018), permitting the present report to examine some broader equity concerns raised both by possible failure to limit warming to 1.5°C and by the range of ambitious mitigation efforts that may be undertaken to achieve that limit. Any comparison between 1.5°C and higher levels of warming implies risk assessments and value judgements, and cannot straightforwardly be reduced to a cost-benefit analysis (Kolstad et al., 2014). However, different levels of warming can nevertheless be understood in terms of their different implications for equity – that is, in the comparative distribution of benefits and burdens for specific states, persons or generations, and in terms of their likely impacts on sustainable development and poverty (see especially sections 2.2.2.3, 2.3.3.1, 3.4.5-3.4.11, 3.6, 5.4.1, 5.4.2, 5.6 and Cross-Chapter boxes 6 in Chapter 3 and 12 in Chapter 5).

1.1.2 Eradication of poverty

This report assesses the role of poverty and its eradication in the context of strengthening the global response to the threat of climate change and sustainable development. A wide range of definitions for *poverty* exist. The AR5 discussed 'poverty' in terms of its multidimensionality, referring to 'material circumstances' (e.g. needs, patterns of deprivation, or limited resources), as well as to economic conditions (e.g. standard of living, inequality, or economic position), and/or social relationships (e.g. social class, dependency, lack of basic security, exclusion, or lack of entitlement – Olsson et al., 2014). The UNDP now uses a Multidimensional Poverty Index, and estimates that about 1.5 billion people globally live in multidimensional poverty, especially in rural areas of South Asia and Sub-Saharan Africa, with an additional billion at risk of falling into poverty (UNDP, 2016).

A large and rapidly growing body of knowledge explores the connections between climate change and poverty. Climatic variability and climate change are widely recognized as factors that may exacerbate poverty, particularly in countries and regions where poverty levels are high (Leichenko and Silva, 2014). The AR5 noted that climate change-driven impacts often act as a threat multiplier in that the impacts of climate change compound other drivers of poverty (Olsson et al., 2014). Many vulnerable and poor people are dependent on activities such as agriculture that are highly susceptible to temperature increases and variability in precipitation patterns (Shiferaw et al., 2014; Miyan, 2015). Even modest changes in rainfall and temperature patterns can push marginalized people into poverty as they lack the means to recover from shocks. Extreme events, such as floods, droughts, and heat waves, especially when they occur in series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labour productivity, housing, infrastructure, and social networks (Olsson et al., 2014).

1.1.3 Sustainable development and a 1.5°C warmer world

AR5 noted with *high confidence* that 'equity is an integral dimension of sustainable development' and that 'mitigation and adaptation measures can strongly affect broader sustainable development and equity objectives' (Fleurbaey et al., 2014). Limiting global warming to 1.5°C will require substantial societal and technological transformations, dependent in turn on global and regional sustainable development pathways. A range of pathways, both sustainable and not, are explored in this report, including implementation strategies to understand the enabling conditions and challenges required for such a transformation. These pathways and connected strategies are framed within the context of sustainable development, and in particular the United Nations 2030 Agenda for Sustainable Development (UNGA, 2015) and Cross-Chapter Box 4 on SDGs (in this Chapter). The feasibility of staying within 1.5°C depends upon a range of enabling conditions with geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional enabling conditions. Limiting warming to 1.5°C also involves identifying technology and policy levers to accelerate the pace of transformation (see Chapter 4). Some pathways are more consistent than others with the requirements for sustainable development (see Chapter 5). Overall, the three-pronged emphasis on sustainable development, resilience, and transformation provides Chapter 5 an opportunity to assess the conditions of simultaneously reducing societal vulnerabilities, addressing entrenched inequalities, and breaking the circle of poverty.

The feasibility of any global commitment to a 1.5°C pathway depends, in part, on the cumulative influence of the nationally determined contributions (NDCs), committing nation states to specific GHG emission reductions. The current NDCs, extending only to 2030, do not limit warming to 1.5°C. Depending on mitigation decisions after 2030, they cumulatively track toward a warming of 3-4°C above preindustrial temperatures by 2100, with the potential for further warming thereafter (Rogelj et al., 2016a; UNFCCC, 2016). The analysis of pathways in this report reveals opportunities for greater decoupling of economic growth from GHG emissions. Progress towards limiting warming to 1.5°C requires a significant acceleration of this trend. AR5 (IPCC, 2014a) concluded that climate change constrains possible development paths, that synergies and trade-offs exist between climate responses and socio-economic contexts, and that opportunities for effective climate responses overlap with opportunities for sustainable development, noting that many existing societal patterns of consumption are intrinsically unsustainable (Fleurbaey et al., 2014).

1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization

1.2.1 Working definitions of 1.5°C and 2°C warming relative to pre-industrial levels

What is meant by 'the increase in global average temperature … above pre–industrial levels' referred to in the Paris Agreement depends on the choice of pre–industrial reference period, whether 1.5°C refers to total warming or the human–induced component of that warming, and which variables and geographical coverage are used to define global average temperature change. The cumulative impact of these definitional ambiguities (e.g. Hawkins et al., 2017; Pfleiderer et al., 2018) is comparable to natural multi–decadal temperature variability on continental scales (Deser et al., 2012) and primarily affects the historical period, particularly that prior to the early 20th century when data is sparse and of less certain quality. Most practical mitigation and adaptation decisions do not depend on quantifying historical warming to this level of precision, but a consistent working definition is necessary to ensure consistency across chapters and figures. We adopt definitions that are as consistent as possible with key findings of AR5 with respect to historical warming.

This report defines 'warming', unless otherwise qualified, as an increase in multi-decade global mean surface temperature (GMST) above pre–industrial levels. Specifically, warming at a given point in time is defined as the global average of combined land surface air and sea surface temperatures for a 30–year period centred on that time, expressed relative to the reference period 1850-1900 (adopted for consistency with Box SPM.1 Figure 1 of IPCC (2014e) 'as an approximation of pre–industrial levels', excluding the impact of natural climate fluctuations within that 30–year period and assuming any secular trend continues throughout that period, extrapolating into the future if necessary. There are multiple ways of accounting for natural fluctuations and trends (e.g., Foster and Rahmstorf, 2011; Haustein et al., 2017; Medhaug et al., 2017), but all give similar results. A major volcanic eruption might temporarily reduce observed global temperatures, but would not reduce warming as defined here (Bethke et al., 2017). Likewise, given that the level of warming is currently increasing at 0.3-0.7°C per 30 years (Kirtman et al., 2013), the level of warming in 2017 is 0.15-0.35°C higher than average warming over the 30–year period 1988-2017.

In summary, this report adopts a working definition of '1.5°C relative to pre–industrial levels' that corresponds to global average combined land surface air and sea surface temperatures either 1.5°C warmer than the average of the 51-year period 1850-1900, 0.87°C warmer than the 20-year period 1986–2005, or 0.63°C warmer than the decade 2006–2015. These offsets are based on all available published global datasets, combined and updated, which show that 1986-2005 was 0.63°C (±0.06°C 5–95% range based on observational uncertainties alone), and 2006-2015 was 0.87°C (±0.12°C *likely* range also accounting for the possible impact of natural fluctuations), warmer than 1850–1900. Where possible, estimates of impacts and mitigation pathways are evaluated relative to these more recent periods.

1.2.1.1 Definition of global average temperature

The IPCC has traditionally defined changes in observed GMST as a weighted average of near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans (Morice et al., 2012; Hartmann et al., 2013), while modelling studies have typically used a simple global average SAT. For ambitious mitigation goals, and under conditions of rapid warming, the difference can be significant. Cowtan et al. (2015) and Richardson et al. (2016) show that the use of blended SAT/SST data and incomplete coverage together can give approximately 0.2°C less warming from the 19th century to the present relative to the use of complete global-average SAT (Stocker et al. , 2013), Figure TFE8.1 and Figure 1.2). However, Richardson et al. (2018) show that this is primarily an issue for the interpretation of the historical record to date, not for projection of future changes or for estimated emissions budgets consistent with future changes, particularly under ambitious mitigation scenarios.

The three GMST reconstructions used in AR5 differ in their treatment of missing data. GISTEMP (Hansen et al., 2010) uses interpolation to infer trends in poorly-observed regions like the Arctic (although even this product is spatially incomplete in the early record), while NOAA (Vose et al., 2012) and HadCRUT (Morice et al., 2012) are progressively closer to a simple average of available observations. Since the AR5, considerable effort has been devoted to more sophisticated statistical modelling to account for the impact of incomplete observation coverage (Rohde et al., 2013; Cowtan and Way, 2014; Jones, 2016). The main impact of statistical infilling is to increase estimated warming to date by about 0.1°C (Richardson et al., 2018 and Table 1.1).

We adopt a working definition of warming over the historical period based on an average of the four available global datasets that are supported by peer-reviewed publications: the three datasets used in the AR5, updated (Karl et al., 2015), together with the Cowtan-Way infilled dataset (Cowtan and Way, 2014). A further two datasets, Berkeley Earth (Rohde et al., 2013) and JMA, are provided in Table 1.1. This working definition provides an updated estimate of 0.86°C for the warming 1880-2012 based on a linear trend that was quoted as 0.85°C in the AR5. Hence the inclusion of the Cowtan-Way dataset does not introduce any inconsistency with the AR5, whereas redefining GMST to represent global SAT could increase this figure by up to 20%, (Table 1.1, Figure 1.2 Richardson et al., 2016).

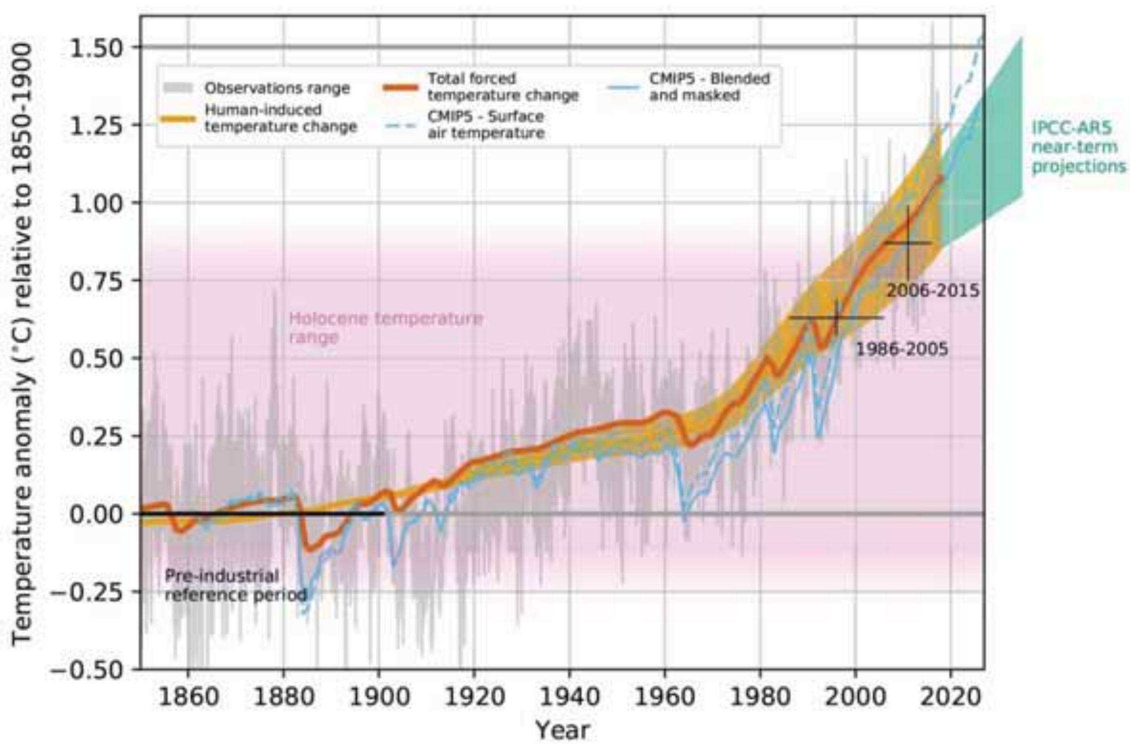

Figure 1.2: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Grey line shows monthly mean GMST in the HadCRUT4, NOAA, GISTEMP and Cowtan-Way datasets, expressed as departures from 1850–1900, with line thickness indicating inter–dataset range. All observational datasets shown represent GMST as a weighted average of near surface air temperature over land and sea surface temperature over oceans. Human–induced (yellow) and total (human– and naturally–forced, orange) contributions to these GMST changes

are shown calculated following Otto et al. (2015) and Haustein et al. (2017). Fractional uncertainty in the level of human–induced warming in 2017 is set equal to ±20%. Thin blue lines show the modelled global–mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 historical ensemble average extended with RCP8.5 forcing (Cowtan et al., 2015; Richardson et al., 2018). The pink shading indicates a range for temperature fluctuations over the Holocene (Marcott et al., 2013). Light green plume shows AR5 prediction for average GMST over 2016–2035 (Kirtman et al., 2013). See Technical Annex 1.A of this chapter for further details.

1.2.1.2 Choice of reference period

Any choice of reference period used to approximate 'pre–industrial' conditions is a compromise between data coverage and representativeness of typical pre-industrial solar and volcanic forcing conditions. This report adopts the 51-year reference period, 1850–1900 inclusive, assessed as an approximation of pre-industrial conditions in AR5 (Box TS.5, Figure 1 of Field et al., 2014). The years 1880–1900 are subject to strong but uncertain volcanic forcing, but in the HadCRUT4 dataset, average temperatures over 1850–1879, prior to the largest eruptions, are less than 0.01°C from the average for 1850–1900. Temperatures rose by 0.0–0.2°C from 1720–1800 to 1850–1900 (Hawkins et al., 2017), but the anthropogenic contribution to this warming is uncertain (Schurer et al., 2017). The 18th century represents a relatively cool period in the context of temperatures since the mid-Holocene (Marcott et al., 2013; Marsicek et al., 2018), as indicated by the pink shaded region in Figure 1.2.

Projections of responses to emission scenarios, and associated impacts, may use a more recent reference period, offset by historical observations, to avoid conflating uncertainty in past and future changes (e.g. Hawkins et al., 2017; Millar et al., 2017b; Simmons et al., 2017). Two recent reference periods are used in this report: 1986–2005 and 2006–2015. In the latter case, when using a single decade to represent a 30-year average centred on that decade, it is important to consider the potential impact of internal climate variability. The years 2008–2013 were characterised by persistent cool conditions in the Eastern Pacific (Kosaka and Xie, 2013; Medhaug et al., 2017), related to both the El Niño / Southern Oscillation (ENSO) and, potentially, multi–decadal Pacific variability (e.g., England et al., 2014), but these were partially compensated for by El Niño conditions in 2006 and 2015. Likewise, volcanic activity depressed temperatures in 1986–2005, partly offset by the very strong El Niño event in 1998. Figure 1.2 indicates that natural variability (internally generated and externally driven) had little net impact on average temperatures over 2006–2015, in that the average temperature of the decade is similar to the estimated externally–driven warming. When solar, volcanic and ENSO-related variability is taken into account following the procedure of Foster and Rahmstorf (2011), there is no indication of average temperatures in either 1986–2005 or 2006–2015 being substantially biased by short-term variability (see Technical Appendix). The temperature difference between these two reference periods (0.21–0.27°C over 15 years across available datasets) is also consistent with the AR5 assessment of the current warming rate of 0.3–0.7°C over 30 years (Kirtman et al., 2013).

On the definition of warming used here, warming to the decade 2006–2015 comprises an estimate of the 30-year average centered on this decade, or 1996–2025, assuming the current trend continues and that any volcanic eruptions that might occur over the final seven years are corrected for. Given this element of extrapolation, we use the AR5 near-term projection to provide a conservative uncertainty range. Combining the uncertainty in observed warming to 1986–2005 (±0.06°C) with the *likely* range in the current warming trend as assessed by AR5 (±0.2°C/30 years), assuming these are uncorrelated, and using observed warming relative to 1850–1900 to provide the central estimate (no evidence of bias from short-term variability), gives an assessed warming to the decade 2006–2015 of 0.87°C with a ±0.12°C *likely* range. This estimate has the advantage of traceability to the AR5, but more formal methods of quantifying externally-driven warming (e.g., Bindoff et al., 2013; Jones et al., 2016; Haustein et al., 2017; Ribes et al., 2017), which typically give smaller ranges of uncertainty, may be adopted in future.

Table 1.1: Observed increase in global average surface temperature in various datasets. Numbers in square brackets correspond to 5-95% uncertainty ranges from individual datasets, encompassing known sources of observational uncertainty only.

Diagnostic / dataset	1850-1900 to (1) 2006-2015	1850-1900 to (2) 1986-2005	1986-2005 to (3) 2006-2015	1850-1900 to (4) 1981-2010	1850-1900 to (5) 1998-2017	trend (6) 1880-2012	trend (6) 1880-2015
HadCRUT4.6	0.84 [0.79—0.89]	0.60 [0.57—0.66]	0.22 [0.21—0.23]	0.62 [0.58—0.67]	0.83 [0.78—0.88]	0.83 [0.77—0.90]	0.88 [0.83—0.95]
NOAA (7)	0.86	0.62	0.22	0.63	0.85	0.85	0.91
GISTEMP (7)	0.89	0.65	0.23	0.66	0.88	0.89	0.94
Cowtan-Way	0.91 [0.85—0.99]	0.65 [0.60—0.72]	0.26 [0.25—0.27]	0.65 [0.60—0.72]	0.88 [0.82—0.96]	0.88 [0.79—0.98]	0.93 [0.85—1.03]
Average (8)	**0.87**	0.63	0.23	0.64	0.86	0.86	0.92
Berkeley (9)	0.98	0.73	0.25	0.73	0.97	0.97	1.02
JMA (9)	0.82	0.59	0.17	0.60	0.81	0.82	0.87
ERA-Interim	N/A	N/A	0.26	N/A	N/A	N/A	N/A
JRA-55	N/A	N/A	0.23	N/A	N/A	N/A	N/A
CMIP5 global SAT (10)	0.99 [0.65—1.37]	0.62 [0.38—0.94]	0.38 [0.24—0.62]	0.62 [0.34—0.93]	0.89 [0.62—1.29]	0.81 [0.58—1.31]	0.86 [0.63—1.39]
CMIP5 SAT/SST blend—masked	0.86 [0.54—1.18]	0.50 [0.31—0.79]	0.34 [0.19—0.54]	0.48 [0.26—0.79]	0.75 [0.52—1.11]	0.68 [0.45—1.08]	0.74 [0.51—1.14]

Notes:
1) Most recent reference period used in this report.
2) Most recent reference period used in AR5.
3) Difference between recent reference periods.
4) Current WMO standard reference periods.
5) Most recent 20-year period.
6) Linear trends estimated by a straight-line fit, expressed in degrees yr^{-1} multiplied by 133 or 135 years respectively, with uncertainty ranges incorporating observational uncertainty only.
7) To estimate changes in the NOAA and GISTEMP datasets relative to the 1850–1900 reference period, warming is computed relative to 1850–1900 using the HadCRUT4.6 dataset and scaled by the ratio of the linear trend 1880–2015 in the NOAA or GISTEMP dataset with the corresponding linear trend computed from HadCRUT4.
8) Average of diagnostics derived – see (7) – from four peer-reviewed global datasets, HadCRUT4.6, NOAA, GISTEMP & Cowtan-Way. Note that differences between averages may not coincide with average differences because of rounding.
9) No peer-reviewed publication available for these global combined land-sea datasets.
10) CMIP5 changes estimated relative to 1861–80 plus 0.02°C for the offset in HadCRUT4.6 from 1850–1900. CMIP5 values are the mean of the RCP8.5 ensemble, with 5–95% ensemble range. They are included to illustrate the difference between a complete global surface air temperature record (SAT) and a blended surface air and sea surface temperature (SST) record accounting for incomplete coverage (masked), following Richardson et al. (2016). Note that 1986–2005 temperatures in CMIP5 appear to have been depressed more than observed temperatures by the eruption of Mount Pinatubo.

1.2.1.3 Total versus human–induced warming and warming rates

Total warming refers to the actual temperature change, irrespective of cause, while human–induced warming refers to the component of that warming that is attributable to human activities. Mitigation studies focus on human-induced warming (that is not subject to internal climate variability), while studies of climate change impacts typically refer to total warming (often with the impact of internal variability minimised through the use of multi–decade averages).

In the absence of strong natural forcing due to changes in solar or volcanic activity, the difference between total and human-induced warming is small: assessing empirical studies quantifying solar and volcanic contributions to GMST from 1890 to 2010, AR5 (Fig. 10.6 of Bindoff et al., 2013) found their net impact on warming over the full period to be less than ±0.1°C. Figure 1.2 shows that the level of human–induced warming has been indistinguishable from total observed warming since 2000, including over the decade 2006–2015. Bindoff et al. (2013) assessed the magnitude of human-induced warming over the period 1951–2010 to be 0.7°C±0.1°C, slightly greater than the 0.65°C observed warming over this period (Figures 10.4 & 10.5) and a *likely* range of ±14%. The key surface temperature attribution studies underlying this finding finding (Gillett et al., 2013; Jones et al., 2013; Ribes and Terray, 2013) used temperatures since the 19th century to constrain human-induced warming, and so their results are equally applicable to the attribution of causes of warming over longer periods. Jones et al. (2016) show (Figure 10) human-induced warming trends over the period 1905–2005 to be indistinguishable from the corresponding total observed warming trend accounting for natural variability using spatio-temporal detection patterns from 12 out of 15 CMIP5 models and from the multi-model average. Figures from Ribes and Terray (2013), show the anthropogenic contribution to the observed linear warming trend 1880-2012 in the HadCRUT4 dataset (0.83°C in Table 1.1) to be 0.86°C using a multi-model average global diagnostic, with a 5-95% confidence interval of 0.72-1.00°C. In all cases, since 2000 the estimated combined contribution of solar and volcanic activity to warming relative to 1850–1900 is found to be less than ±0.1°C (Gillett et al., 2013), while anthropogenic warming is indistinguishable from, and if anything slightly greater than, the total observed warming, with 5–95% confidence intervals typically around ±20%.

Haustein et al. (2017) give a 5–95% confidence interval for human-induced warming in 2017 of 0.87–1.22°C, with a best estimate of 1.02°C, based on the HadCRUT4 dataset accounting for observational and forcing uncertainty and internal variability. Applying their method to the average of the 4 datasets shown in figure 1.2 gives an average level of human-induced warming in 2017 of 1.04°C. They also estimate a human-induced warming trend over the past 20 years of 0.17°C (0.13–0.33°C) per decade, consistent with estimates of the total observed trend of Foster and Rahmstorf (2011) (0.17±0.03°C/decade uncertainty in linear trend only) and Kirtman et al. (2013) (0.3–0.7°C over 30 years, or 0.1–0.23°C/decade, *likely* range), and a best-estimate warming rate over the past five years of 0.215°C/decade (Leach et al., 2018). Drawing on these multiple lines of evidence, human-induced warming is assessed to have reached 1.0°C in 2017, having increased by 0.13°C from the mid-point of 2006–2015, with a *likely* range of ±0.2°C (reduced from 5–95% to account for additional forcing and model uncertainty), increasing at 0.2°C (±0.1°C) per decade (estimates of human-induced warming given to 0.1°C precision only).

Since warming is here defined in terms of a 30-year average, corrected for short-term natural fluctuations, when warming is considered to be at 1.5°C, global temperatures would fluctuate equally on either side of 1.5°C in the absence of a large cooling volcanic eruption (Bethke et al, 2017). Figure 1.2 indicates there is a substantial chance of GMST in a single month fluctuating over 1.5°C between now and 2020, but this would not constitute temperatures 'reaching 1.5°C' on our working definition. Rogelj et al. (2017) show limiting the probability of annual GMST exceeding 1.5°C to less than one-year-in-20 would require limiting warming, on the definition used here, to 1.31°C or lower.

1.2.2 Global versus regional and seasonal warming

Warming is not observed or expected to be spatially or seasonally uniform (IPCC, 2013b). A 1.5°C increase in GMST will be associated with warming substantially greater than 1.5°C in many land regions, and less than 1.5°C in most ocean regions. This is illustrated by Figure 1.3, which shows an estimate of the observed change in annual and seasonal average temperatures between the 1850-1900 pre-industrial reference period and the decade 2006–2015 in the Cowtan-Way dataset. These regional changes are associated with an observed GMST increase of 0.91°C in the dataset shown here, or

0.87°C in the 4-dataset average (Table 1.1). This observed pattern reflects an on-going transient warming: features such as enhanced warming over land may be less pronounced, but still present, in equilibrium (IPCC, 2013b). This figure illustrates the magnitude of these differences, with many locations, particularly in Northern-Hemisphere mid-latitude winter (December–February), already experiencing regional warming more than double the global average. Individual seasons may be substantially warmer, or cooler, than these expected long–term average changes.

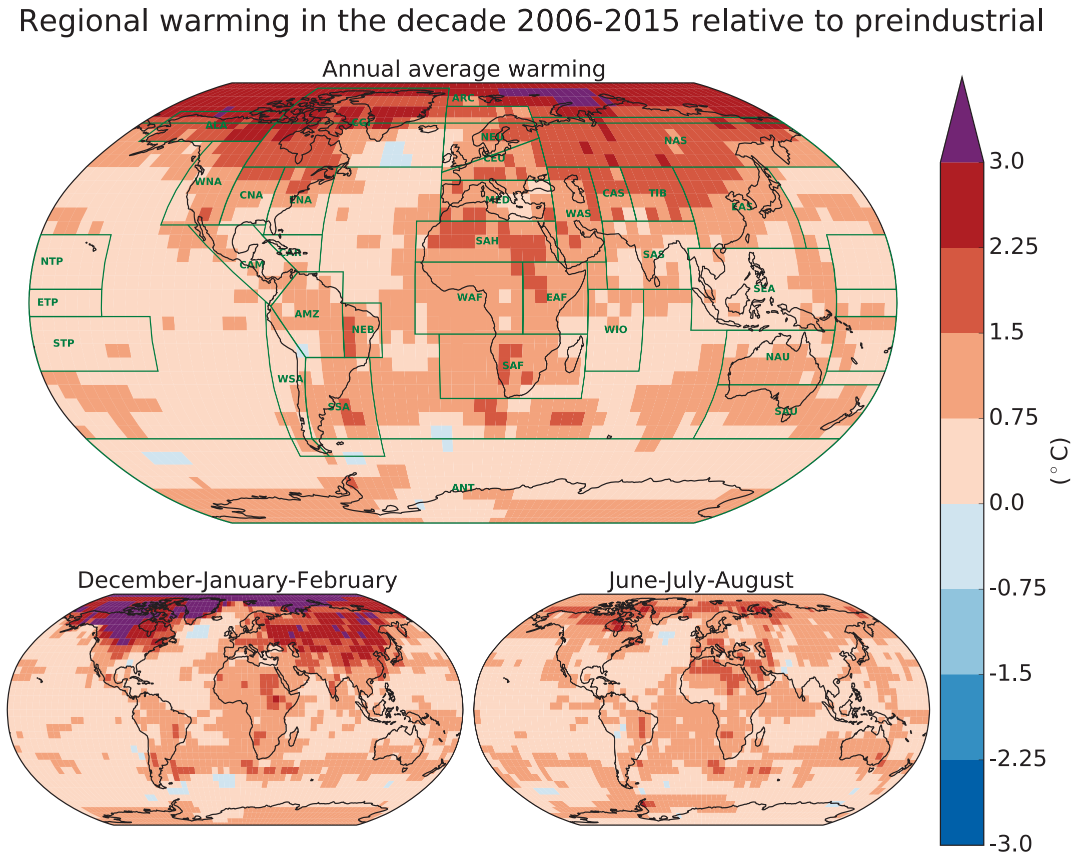

Figure 1.3: Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January and February (bottom left) and for June, July and August (bottom right). Warming is evaluated by regressing regional changes in the (Cowtan and Way, 2014) dataset onto the total (combined human and natural) externally-forced warming (yellow line in Figure 1.2). See Technical Annex 1.A of this chapter for further details and versions using alternative datasets. The definition of regions (green boxes and labels in top panel) is adopted from the AR5 (Christensen et al., 2013).

1.2.3 Definition of 1.5°C-consistent pathways: probability, transience, stabilization and overshoot

Pathways considered in this report, consistent with available literature on 1.5°C, primarily focus on the timescale up to 2100, recognising that the evolution of GMST after 2100 is also important. Two broad categories of 1.5°C-consistent pathways can be used to characterise mitigation options and impacts: pathways in which warming (defined as 30-year averaged GMST relative to pre-industrial levels, see section 1.2.1) remains below 1.5°C throughout the 21st century, and pathways in which warming temporarily exceeds ('overshoots') 1.5°C and returns to 1.5°C either before or soon after

2100. Pathways in which warming exceeds 1.5°C before 2100, but might return to that level in some future century, are not considered 1.5°C-consistent.

Because of uncertainty in the climate response, a 'prospective' mitigation pathway (see Cross-Chapter Box 1 in this Chapter), in which emissions are prescribed, can only provide a level of probability of warming remaining below a temperature threshold. This probability cannot be quantified precisely since estimates depend on the method used (Rogelj et al., 2016b; Millar et al., 2017b; Goodwin et al., 2018; Tokarska and Gillett, 2018). This report defines a '1.5°C-consistent pathway' as a pathway of emissions and associated possible temperature responses in which the majority of approaches using presently-available information assign a probability in the range of approximately one-in-two to two-in-three to warming remaining below 1.5°C or, in the case of an overshoot pathway, returning to 1.5°C by around 2100 or earlier. In Chapter 2, the classification of pathways is based on one modeling approach to avoid ambiguity, but probabilities of exceeding 1.5°C are checked against other approaches to verify that they lie within this approximate range. All these absolute probabilities are imprecise, depend on the information used to constrain them, and hence are expected to evolve in the future. Imprecise probabilities can nevertheless be useful for decision-making, provided the imprecision is acknowledged (Hall et al., 2007; Kriegler et al., 2009; Simpson et al., 2016). Relative and rank probabilities can be assessed much more consistently: approaches may differ on the absolute probability assigned to individual outcomes, but typically agree on which outcomes are more probable.

Importantly, 1.5°C-consistent pathways allow a substantial (up to one-in-two) chance of warming still exceeding 1.5°C. An 'adaptive' mitigation pathway in which emissions are continuously adjusted to achieve a specific temperature outcome (e.g. Millar et al., 2017b) reduces uncertainty in the temperature outcome while increasing uncertainty in the emissions required to achieve it. It has been argued (Otto et al., 2015; Xu and Ramanathan, 2017) that achieving very ambitious temperature goals will require such an adaptive approach to mitigation, but very few studies have been performed taking this approach (e.g. Jarvis et al., 2012).

Figure 1.4 illustrates these categories of (a) 1.5°C-consistent temperature pathways and associated (b) annual and (c) cumulative emissions of CO_2. It also shows (d) a 'time-integrated impact' that continues to increase even after GMST has stabilised, such as sea-level rise. This schematic assumes for illustration that the fractional contribution of non-CO_2 climate forcers to total anthropogenic forcing (which is currently increasing, Myhre et al., 2017) is approximately constant from now on. Consequently, total human-induced warming is proportional to cumulative CO_2 emissions (solid line in c), and GMST stabilises when emissions reach zero. This is only the case in the most ambitious scenarios for non-CO_2 mitigation (Leach et al., 2018). A simple way of accounting for varying non-CO_2 forcing in Figure 1.4 would be to note that every 1 W/m^2 increase in non-CO_2 forcing between now and the decade or two immediately prior to the time of peak warming reduces cumulative CO_2 emissions consistent with the same peak warming by approximately 1200±300 $GtCO_2$ (using values from AR5: Myhre et al, 2013; Jenkins et al, 2018; Allen et al, 2018; Cross-Chapter Box 2 in this Chapter).

1.2.3.1 Pathways remaining below 1.5°C

In this category of 1.5°C-consistent pathways, human-induced warming either rises monotonically to stabilise at 1.5°C (Figure 1.4, brown lines) or peaks at or below 1.5°C and then declines (yellow lines). Figure 1.4, panel b demonstrates that pathways remaining below 1.5°C require net annual CO_2 emissions to peak and decline to near zero or below, depending on the long-term adjustment of the carbon cycle and non-CO_2 emissions (Bowerman et al., 2013; Wigley, 2018). Reducing emissions to zero corresponds to stabilizing cumulative CO_2 emissions (panel c, solid lines) and falling concentrations of CO_2 in the atmosphere (panel c dashed lines) (Matthews and Caldeira, 2008;

Solomon et al., 2009), which is required to stabilize GMST if non-CO_2 climate forcings are constant and positive. Stabilizing atmospheric greenhouse gas concentrations would result in continued warming (see Section 1.2.4).

If starting emission reductions is delayed until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO_2 emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO_2 forcing, and also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year's delay before initiating emission reductions reduces by approximately two years the remaining time available to reduce emissions to zero on a pathway remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018).

1.2.3.2 Pathways temporarily exceeding 1.5°C

With the pathways in this category, also referred to as overshoot pathways, GMST rises above 1.5°C before peaking and returning to 1.5°C around or before 2100 (Figure 1.4, blue lines), subsequently either stabilising or continuing to fall. This allows initially slower or delayed emission reductions but lowering GMST requires net negative global CO_2 emissions (net anthropogenic removal of CO_2; Figure 1.4, panel b). Cooling, or reduced warming, through sustained reductions of net non-CO_2 climate forcing (Cross-Chapter Box 2 in this Chapter) is also required, but their role is limited because emissions of most non-CO_2 forcers cannot be reduced to below zero. Hence the feasibility and availability of large–scale CO_2 removal limits the possible rate and magnitude of temperature decline. In this report, overshoot pathways are referred to as 1.5°C-consistent, but qualified by the amount of the temperature overshoot, which can have a substantial impact on irreversible climate change impacts (Mathesius et al., 2015; Tokarska and Zickfeld, 2015).

1.2.3.3 Impacts at 1.5°C warming associated with different pathways: transience versus stabilisation

Figure 1.4 also illustrates timescales associated with different impacts. While many impacts scale with the change in GMST itself, some (such as those associated with ocean acidification) scale with the change in atmospheric CO_2 concentration, indicated by the fraction of cumulative CO_2 emissions remaining in the atmosphere (dotted lines in panel c). Others may depend on the rate of change of GMST, while 'time-integrated impacts', such as sea-level rise, shown in panel (d) continue to increase even after GMST has stabilised.

Hence impacts that occur when GMST reaches 1.5°C could be very different depending on the pathway to 1.5°C. CO_2 concentrations will be higher as GMST rises past 1.5°C (transient warming) than when GMST has stabilized at 1.5°C while sea level and, potentially, global mean precipitation (Pendergrass et al., 2015) would both be lower (see Figure 1.4). These differences could lead to very different impacts on agriculture, on some forms of extreme weather (e.g., Baker et al., 2018), and on marine and terrestrial ecosystems (e.g., Mitchell et al., 2017,)Box 3.1). Sea level would be higher still if GMST returns to 1.5°C after an overshoot (Figure 1.4, panel d), with potentially significantly different impacts in vulnerable regions. Temperature overshoot could also cause irreversible impacts (see Chapter 3).

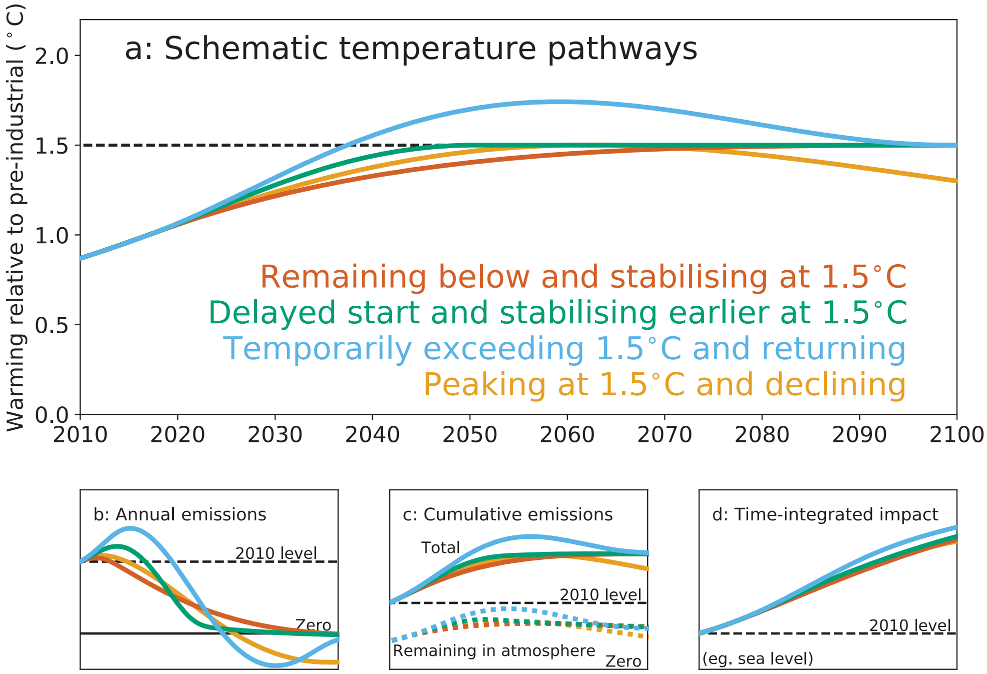

Figure 1.4: **Different 1.5°C-consistent pathways[1]:** Schematic illustration of the relationship between (a) global mean surface temperature (GMST) change; (b) annual rates of CO_2 emissions, assuming constant fractional contribution of non-CO_2 forcing to total human-induced warming; (c) total cumulative CO_2 emissions (solid lines) and the fraction thereof remaining in the atmosphere (dashed lines; these also indicates changes in atmospheric CO_2 concentrations); and (d) a time-integrated impact, such as sea-level rise, that continues to increase even after GMST has stabilized. Colours indicate different 1.5°C-consistent pathways. Brown: GMST remaining below and stabilizing at 1.5°C in 2100; Green: a delayed start but faster implementation pathway with GMST remaining below and reaching 1.5°C earlier; Blue: a pathway temporarily exceeding 1.5°C, with temperatures reduced to 1.5°C by net negative CO_2 emissions after temperatures peak; and Yellow: a pathway peaking at 1.5°C and subsequently declining. Temperatures are anchored to 0.87°C above pre–industrial in 2010; emissions–temperature relationships are computed using a simple climate model (Myhre et al., 2013; Millar et al., 2017a; Jenkins et al., 2018) with a lower value of the Transient Climate Response (TCR) than used in the quantitative pathway assessments in Chapter 2 to illustrate qualitative differences between pathways: this figure is not intended to provide quantitative information. The time-integrated impact is illustrated by the semi-empirical sea–level–rise model of Kopp et al. (2016).

[1] FOOTNOTE: An animated version of Figure 1.4 will be embedded in the web-based version of this Special Report

Cross-Chapter Box 1: Scenarios and Pathways

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Climate change scenarios have been used in IPCC assessments since the First Assessment Report (Leggett et al., 1992). The **SRES scenarios** (named after the IPCC Special Report on Emissions Scenarios; IPCC, 2000), published in 2000, consist of four scenarios that do not take into account any future measures to limit greenhouse gas (GHG) emissions. Subsequently, many policy scenarios have been developed based upon them (Morita et al., 2001). The SRES scenarios are superseded by a set of scenarios based on the Representative Concentration Pathways (RCPs) and Shared Socio–Economic Pathways (SSPs) (Riahi et al., 2017). The RCPs comprise a set of four GHG concentration trajectories that jointly span a large range of plausible human–caused climate forcing ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century (van Vuuren et al., 2011). They were used to develop climate projections in the 5th Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) and were assessed in the IPCC 5th Assessment Report (AR5). Based on the CMIP5 ensemble, RCP2.6, provides a better than two in three chance of staying below 2°C and a median warming of 1.6°C relative to 1850–1900 in 2100 (Collins et al., 2013).

The SSPs were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation. SSP-based scenarios were developed for a range of climate forcing levels, including the end-of-century forcing levels of the RCPs (Riahi et al., 2017) and a level below RCP2.6 to explore pathways limiting warming to 1.5°C above pre–industrial levels (Rogelj et al., 2018). The SSP-based 1.5°C-consistent pathways are assessed in Chapter 2 of this report. These scenarios offer an integrated perspective on socio–economic, energy-system (Bauer et al., 2017), land use (Popp et al., 2017), air pollution (Rao et al., 2017) and GHG emissions developments (Riahi et al., 2017). Because of their harmonised assumptions, scenarios developed with the SSPs facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.

Scenarios and Pathways in this Report

This report focuses on pathways that could limit the increase of global mean surface temperature (GMST) to 1.5°C above pre–industrial levels and pathways that align with the goals of sustainable development and poverty eradication. Pace and scale of mitigation and adaptation are assessed in the context of historical evidence to determine where unprecedented change is required (see Chapter 4). Other scenarios are also assessed, primarily as benchmarks for comparison of mitigation, impacts, and/or adaptation requirements. These include baseline scenarios that assume no climate policy; scenarios that assume some kind of continuation of current climate policy trends and plans, many of which are used to assess the implications of the nationally-determined contributions (NDCs); and scenarios holding warming below 2°C above pre–industrial levels. This report assesses the spectrum from global mitigation scenarios to local adaptation choices – complemented by a bottom-up assessment of individual mitigation and adaptation options and their implementation (policies, finance, institutions, governance, see Chapter 4). Regional, national, and local scenarios, as well as decision-making processes over values and difficult trade-offs are important for understanding the challenges of limiting GMST increase to 1.5°C and are thus indispensable when assessing implementation.

Different climate policies result in different temperature pathways, which result in different levels of climate risks and actual climate impacts with associated long-term implications. Temperature pathways are classified into continued warming pathways (in the cases of baseline and reference scenarios), pathways that keep the temperature below a specific limit (like 1.5°C or 2°C), and pathways that temporarily exceed and later fall to a specific limit (overshoot pathways). In the case of a temperature overshoot, net negative CO_2 emissions are required to remove excess CO_2 from the atmosphere.

In a 'prospective' mitigation pathway, emissions (or sometimes concentrations) are prescribed, giving a range of GMST outcomes because of uncertainty in the climate response. Prospective pathways are considered '1.5°C-consistent' in this report if, based current knowledge, the majority of available approaches assign an approximate probability of one-in-two to two-in-three to temperatures either remaining below 1.5°C or returning to 1.5°C either before or around 2100. Most pathways assessed in Chapter 2 are prospective pathways, and therefore even '1.5°C-consistent pathways' are also associated with risks of warming higher than 1.5°C, noting that many risks increase non-linearly with increasing GMST. In contrast, the 'risks of warming of 1.5°C'assessed in Chapter 3 refer to risks in a world in which GMST is either passing through (transient) or stabilized at 1.5°C, without considering probabilities of different GMST levels (unless otherwise qualified). To stay below any desired temperature limit, adjusting mitigation measures and strategies would be required as knowledge of the climate response is updated (Millar et al., 2017b; Emori et al., 2018). Such pathways can be called 'adaptive' mitigation pathways. Given there is always a possibility of a greater-than-expected climate response (Xu and Ramanathan, 2017), adaptive mitigation pathways are important to minimise climate risks, but need also to consider the risks and feasibility (see Cross-Chapter Box 3 in this Chapter) of faster-than-expected emission reductions. Aligning mitigation and adaptation pathways with sustainable development pathways and transformative visions for the future that would support avoiding negative impacts on the poorest and most disadvantaged populations and vulnerable sectors are assessed in Chapter 5.

Definitions of Scenarios and Pathways

Climate scenarios and pathways are terms that are sometimes used interchangeably, with a wide range of overlapping definitions (Rosenbloom, 2017).

A '**scenario'** is an internally consistent, plausible, and integrated description of a possible future of the human–environment system, including a narrative with qualitative trends and quantitative projections (IPCC, 2000). Climate change scenarios provide a framework for developing and integrating emissions, climate change and climate impact projections, including an assessment of their inherent uncertainties. The long-term and multi–faceted nature of climate change requires climate scenarios to describe how assumptions about inherently uncertain socio-economic trends in the 21st century could influence future energy and land use, resulting in emissions, and climate change as well as human vulnerability and exposure to climate change. Such driving forces include population, GDP, technological innovation, governance, and lifestyles. Climate change scenarios are used for analysing and contrasting climate policy choices.

The notion of a **'pathway'** can have multiple meanings in the climate literature. It is often used to describe the temporal evolution of a set of scenario features, such as GHG emissions and socioeconomic development. As such, it can describe individual scenario components or sometimes be used interchangeably with the word 'scenario'. For example, the RCPs describe GHG concentration trajectories (van Vuuren et al., 2011) and the SSPs are a set of narratives of societal futures augmented by quantitative projections of socio-economic determinants such as population, GDP, and urbanization (Kriegler et al., 2012; O'Neill et al., 2014). Socio-economic driving forces consistent with any of the SSPs can be combined with a set of climate policy assumptions (Kriegler et al., 2014) that together would lead to emissions and concentration outcomes consistent with the RCPs (Riahi et al., 2017). This is at the core of the scenario framework for climate change research that aims to facilitate creating scenarios integrating emissions and development pathways dimensions (Ebi et al., 2014; van Vuuren et al., 2014).

In other parts of the literature, 'pathway' implies a solution-oriented trajectory describing a pathway from today's world to achieving a set of future goals. **Sustainable Development Pathways** describe national and global pathways where climate policy becomes part of a larger sustainability transformation (Shukla and Chaturvedi, 2013; Fleurbaey et al., 2014; van Vuuren et al., 2015). The AR5 presented **climate-resilient pathways** as sustainable development pathways that combine the goals of adaptation and mitigation (Denton et al., 2014), more broadly defined as iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change (IPCC, 2014b). The AR5 also introduced the notion of **climate-resilient development pathways,** with a more explicit focus on dynamic livelihoods, multidimensional poverty, structural inequalities, and equity among poor and non-poor people (Olsson et al., 2014). **Adaptation pathways**, understood as a series of adaptation choices involving trade-offs between short-term and long-term goals and values (Reisinger et al., 2014). They are decision-making processes sequenced over time with the purpose of deliberating and identifying socially-salient solutions in specific places (Barnett et al., 2014; Wise et al., 2014; Fazey et al., 2016). There is a range of possible pathways for transformational change, often negotiated through iterative and inclusive processes (Harris et al., 2017; Fazey et al., 2018; Tàbara et al., 2018).

1.2.4 Geophysical warming commitment

It is frequently asked whether limiting warming to 1.5°C is 'feasible' (Cross–Chapter Box 3 in this Chapter). There are many dimensions to this question, including the warming 'commitment' from past emissions of greenhouse gases and aerosol precursors. Quantifying commitment from past emissions is complicated by the very different behaviour of different climate forcers affected by human activity: emissions of long-lived greenhouse gases such as CO_2 and nitrous oxide (N_2O) have a very persistent impact on radiative forcing (Myhre et al., 2013), lasting from over a century (in the case of N_2O) to hundreds of thousands of years (for CO_2). Short-lived climate forcers (SLCFs) such as methane (CH_4) and aerosols, in contrast, persist for at most about a decade (in the case of methane) down to only a few days. These different behaviours must be taking into account in assessing the implications of any approach to calculating aggregate emissions (Cross-Chapter Box 2 in this Chapter).

Geophysical warming commitment is defined as the unavoidable future warming resulting from physical Earth system inertia. Different variants are discussed in the literature, including (i) the 'constant composition commitment' (CCC), defined by Meehl et al. (2007) as the further warming that would result if atmospheric concentrations of GHGs and other climate forcers were stabilised at the current level; and (ii) and the 'zero emissions commitment' (ZEC), defined as the further warming that would still occur if all future anthropogenic emissions of greenhouse gases and aerosol precursors were eliminated instantaneously (Meehl et al, 2007; Collins et al., 2013).

The CCC is primarily associated with thermal inertia of the ocean (Hansen et al., 2005), and has led to the misconception that substantial future warming is inevitable (Matthews and Solomon, 2013). The CCC takes into account the warming from past emissions, but also includes warming from future emissions (declining but still non-zero) that are required to maintain a constant atmospheric composition. It is therefore not relevant to the warming commitment from past emissions alone.

The ZEC, although based on equally idealised assumptions, allows for a clear separation of the response to past emissions from the effects of future emissions. The magnitude and sign of the ZEC depend on the mix of GHGs and aerosols considered. For CO_2, which has an effective atmospheric residence time of centuries to millennia (Eby et al., 2009), the multi-century warming commitment from emissions to date is estimated to range from slightly negative (i.e., a slight cooling relative to present-day) to slightly positive (Matthews and Caldeira, 2008; Lowe et al., 2009; Gillett et al., 2011; Collins et al., 2013). Some studies estimate a larger ZEC from CO_2, but for cumulative emissions much higher than those up to present day (Frölicher et al., 2014; Ehlert and Zickfeld, 2017). The ZEC from past CO_2 emissions is small because the continued warming effect from ocean thermal inertia is approximately balanced by declining radiative forcing due to CO_2 uptake by the ocean (Solomon et al., 2009; Williams et al., 2017). Thus, although present-day CO_2-induced warming is irreversible on millennial timescales (without human intervention such as active carbon dioxide removal or solar radiation modification (Section 1.4.1)), past CO_2 emissions do not commit to substantial further warming (Matthews and Solomon, 2013).

For warming SLCFs, meaning those associated with positive radiative forcing such as methane, the ZEC is negative. Eliminating emissions of these substances (also sometimes referred to as short-lived climate pollutants, see Section 4.3.6) results in an immediate cooling relative to the present (Figure 1.5, magenta line) (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017). Cooling SLCFs (those associated with negative radiative forcing) such as sulphate aerosols create a positive ZEC, as elimination of these forcers results in rapid warming (Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Samset et al., 2018). Estimates of the warming commitment from eliminating aerosol emissions are affected by large uncertainties in net aerosol radiative forcing (Myhre et al., 2013, 2017). If present–day emissions of all GHGs (short- and long-lived) and aerosols (including sulphate, nitrate and carbonaceous aerosols) are eliminated (Figure 1.5, yellow line) GMST rises over the following decade. This initial warming is followed by a gradual cooling driven by the decline in radiative forcing of short-lived greenhouse gases (Matthews and Zickfeld, 2012; Collins et al., 2013). Peak warming following elimination of all emissions was assessed at a few tenths of a degree in AR5, and century-scale warming was assessed to change only slightly relative to the time emissions are reduced to zero (Collins et al., 2013). New evidence since AR5 suggests a larger methane forcing (Etminan et al., 2016) but no revision in the range of aerosol forcing (although this remains an active field of research, e.g., Myhre et al., 2017). This revised methane forcing estimate results in a smaller peak warming and a faster temperature decline than assessed in AR5 (Figure 1.5, yellow line).

Expert judgement based on the available evidence (including model simulations, radiative forcing and climate sensitivity) suggests that if all anthropogenic emissions were reduced to zero immediately, any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the next two to three decades, and also *likely* less than 0.5°C on a century timescale.

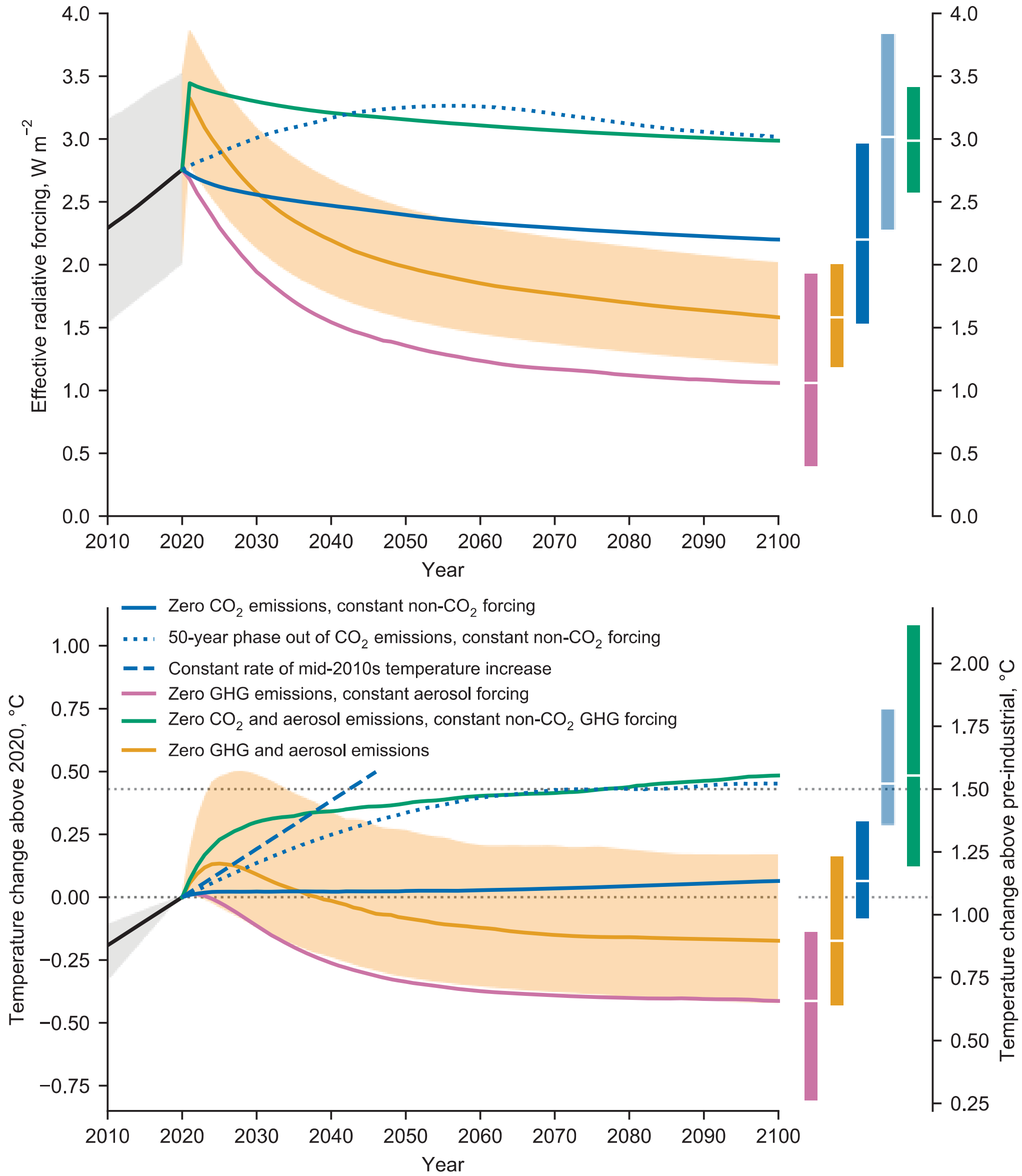

Figure 1.5: Different interpretations of warming commitment from past emissions: Radiative forcing (top) and global mean surface temperature change (bottom) for scenarios with different combinations of greenhouse gas and aerosol precursor emissions reduced to zero in 2020. Variables were calculated using a simple climate–carbon cycle model (Millar et al., 2017a) with a simple representation of atmospheric chemistry (Smith et al., 2018). The bars on the right–hand side indicate the median warming in 2100 and 5–95% uncertainty ranges (also indicated by the plume around the yellow line) taking into account one estimate of uncertainty in climate response, effective radiative forcing, and carbon cycle constraining simple model parameters with response ranges from AR5 combined with historical climate observations (Smith et al., 2018). Temperatures continue to increase slightly after elimination of CO_2 emissions (blue line) due to adjusting to the recent increase in non-CO_2 forcing. The dashed blue line extrapolates one estimate of the current rate of warming, while dotted blue lines show a case where CO_2 emissions are reduced linearly to zero assuming constant non-CO_2 forcing after 2020. Under these highly idealized assumptions, the time to stabilize temperatures at 1.5°C is approximately double the time remaining to reach 1.5°C at the current warming rate.

Since most sources of emissions cannot, in reality, be brought to zero instantaneously due to techno-economic inertia, the current rate of emissions also constitutes a conditional commitment to future emissions and consequent warming depending on achievable rates of emission reductions. The current level and rate of human-induced warming determines both the time left before a temperature threshold is exceeded if warming continues (dashed blue line in Figure 1.5) and the time over which the warming rate must be reduced to avoid exceeding that threshold (approximately indicated by the dotted blue line in Figure 1.5). Leach et al. (2018) use a central estimate of human-induced warming of 1.02°C in 2017 increasing at 0.215°C per decade (Haustein et al., 2017), to argue that it will take 13–32 years (one-standard-error range) to reach 1.5°C if the current warming rate continues, allowing 25–64 years to stabilise temperatures at 1.5°C if the warming rate is reduced at a constant rate of deceleration starting immediately. Since the rate of human-induced warming is proportional to the rate of CO_2 emissions (Matthews et al., 2009; Zickfeld et al., 2009) plus a term approximately proportional to the rate of increase in non–CO_2 radiative forcing (Gregory and Forster, 2008; Allen et al., 2018; Cross-Chapter Box 2 in this Chapter), these timescales also provide an indication of minimum emission reduction rates required if a warming greater than 1.5°C is to be avoided (see Technical Annex 1.A and FAQ 1.2).

Cross-Chapter Box 2: Measuring progress to net zero emissions combining long-lived and short-lived climate forcers

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Emissions of many different climate forcers will affect the rate and magnitude of climate change over the next few decades (Myhre et al., 2013). Since these decades will determine when 1.5°C is reached or whether a warming greater than 1.5°C is avoided, understanding the aggregate impact of different forcing agents is particularly important in the context of 1.5°C-consistent pathways. Paragraph 17 of Decision 1 of the 21st Conference of the Parties on the adoption of the Paris Agreement specifically states that this report is to identify aggregate greenhouse gas emission levels compatible with holding the increase in global average temperatures to 1.5°C above preindustrial levels (see Chapter 2). This request highlights the need to consider the implications of different methods of aggregating emissions of different gases, both for future temperatures and for other aspects of the climate system.

To date, reporting of GHG emissions under the UNFCCC has used Global Warming Potentials (GWPs) evaluated over a 100–year time horizon (GWP_{100}) to combine multiple climate forcers. IPCC Working Group 3 reports have also used GWP_{100} to represent multi-gas pathways (Clarke et al., 2014). For reasons of comparability and consistency with current practice, Chapter 2 in this Special Report continues to use this aggregation method. Numerous other methods of combining different climate forcers have been proposed, such as the Global Temperature-change Potential (GTP; Shine et al., 2005) and the Global Damage Potential (Tol et al., 2012; Deuber et al., 2013).

Climate forcers fall into two broad categories in terms of their impact on global temperature (Smith et al., 2012): long-lived GHGs, such as CO_2 and nitrous oxide (N_2O), whose warming impact depends primarily on the total cumulative amount emitted over the past century or the entire industrial epoch; and short-lived climate forcers (SLCFs), such as methane and black carbon, whose warming impact depends primarily on current and recent annual emission rates (Reisinger et al., 2012; Myhre et al., 2013; Smith et al., 2013; Strefler et al., 2014). These different dependencies affect the emissions reductions required of individual forcers to limit warming to 1.5°C or any other level.

Natural processes that remove CO_2 permanently from the climate system are so slow that reducing the rate of CO_2-induced warming to zero requires net zero global anthropogenic CO_2 emissions (Archer and Brovkin, 2008; Matthews and Caldeira, 2008; Solomon et al., 2009), meaning almost all remaining anthropogenic CO_2 emissions must be compensated for by an equal rate of anthropogenic carbon dioxide removal (CDR). Cumulative CO_2 emissions are therefore an accurate indicator of CO_2-induced warming, except in periods of high negative CO_2 emissions (Zickfeld et al., 2016), and potentially in century-long periods of near-stable temperatures (Bowerman et al., 2011; Wigley, 2018). In contrast, sustained constant emissions of a SLCF such as methane, would (after a few decades) be consistent with constant methane concentrations and hence very little additional methane-induced warming (Allen et al., 2018; Fuglestvedt et al., 2018). Both GWP and GTP would equate sustained SLCF emissions with sustained constant CO_2 emissions, which would continue to accumulate in the climate system, warming global temperatures indefinitely. Hence nominally 'equivalent' emissions of CO_2 and SLCFs, if equated conventionally using GWP or GTP, have very different temperature impacts, and these differences are particularly evident under ambitious mitigation characterising 1.5°C-consistent pathways.

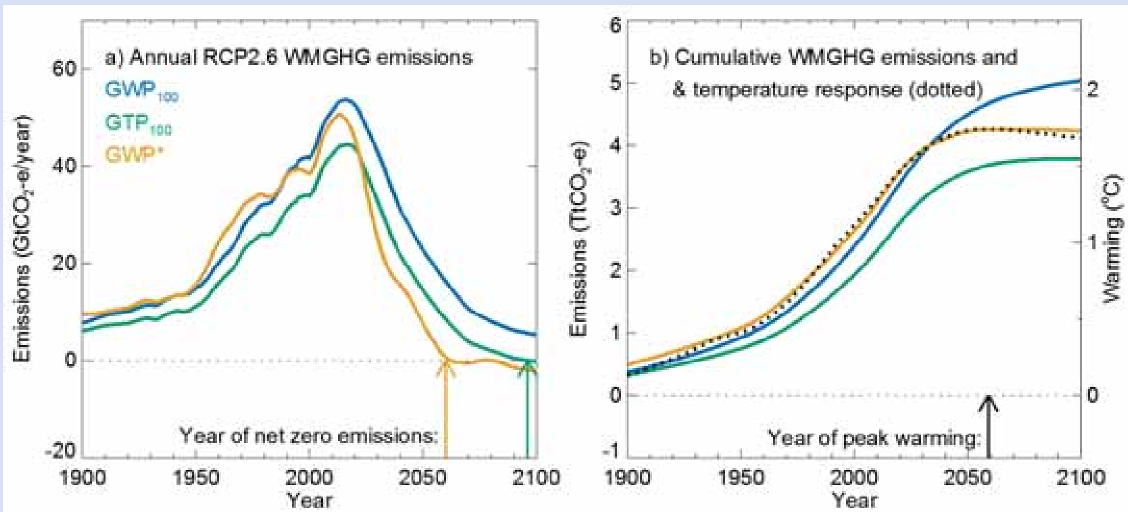
Since the AR5, a revised usage of GWP has been proposed (Lauder et al., 2013; Allen et al., 2016), denoted GWP* (Allen et al., 2018), that addresses this issue by equating a permanently sustained change in the emission *rate* of an SLCF or SLCF-precursor (in tonnes-per-year), or other non-CO_2 forcing (in Watts per square metre), with a one-off *pulse* emission (in tonnes) of a fixed amount of CO_2. Specifically, GWP* equates a 1 tonne-per-year increase in emission rate of an SLCF with a pulse emission of $\mathrm{GWP}_H \times H$ tonnes of CO_2, where GWP_H is the conventional GWP of that SLCF evaluated over time horizon H. While GWP_H for SLCFs decreases with increasing time horizon H, $\mathrm{GWP}_H \times H$ for SLCFs is less dependent on the choice of time horizon. Similarly, a permanent 1 W/m^2 increase in radiative forcing has a similar temperature impact as the cumulative emission of H/AGWP_H tonnes of CO_2, where AGWP_H is the Absolute Global Warming Potential of CO_2 (Shine et al., 2005; Myhre et al., 2013; Allen et al., 2018). This indicates approximately how future changes in non-CO_2 radiative forcing affect cumulative CO_2 emissions consistent with any given level of peak warming.

When combined using GWP*, cumulative aggregate GHG emissions are closely proportional to total GHG-induced warming, while the annual rate of GHG-induced warming is proportional to the annual rate of aggregate GHG emissions (see Cross-Chapter Box 2, Figure 1). This is not the case when emissions are aggregated using GWP or GTP, with discrepancies particularly pronounced when SLCF emissions are falling. Persistent net zero CO_2-equivalent emissions containing a residual positive forcing contribution from SLCFs and aggregated using GWP_{100} or GTP would result in a steady decline of GMST. Net zero global emissions aggregated using GWP* (which corresponds to zero net emissions of CO_2 and other long-lived GHGs like nitrous oxide, combined with constant SLCF forcing – see Figure 1.5) results in approximately stable GMST (Fuglestvedt et al., 2018; Allen et al., 2018 and Cross-Chapter Box 2, Figure 1, below).

Whatever method is used to relate emissions of different greenhouse gases, scenarios achieving stable GMST well below 2°C require both near–zero net emissions of long–lived greenhouse gases and deep reductions in warming SLCFs (Chapter 2), in part to compensate for the reductions in cooling SLCFs that are expected to accompany reductions in CO_2 emissions (Rogelj et al., 2016b; Hienola et al., 2018). Understanding the implications of different methods of combining emissions of different climate forcers is, however, helpful in tracking progress towards temperature stabilisation and 'balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases' as stated in Article 4 of the Paris Agreement. Fuglestvedt et al. (2018) and Tanaka and O'Neill (2018)show that when, and even whether, aggregate GHG emissions need to reach net zero before 2100 to limit warming to 1.5°C depends on the scenario, aggregation method and mix of long-lived and short-lived climate forcers.

The comparison of the impacts of different climate forcers can also consider more than their effects on GMST (Johansson, 2012; Tol et al., 2012; Deuber et al., 2013; Myhre et al., 2013). Climate impacts arise from both magnitude and rate of climate change, and from other variables such as precipitation (Shine et al., 2015). Even if GMST is stabilised, sea-level rise and associated impacts will continue to increase (Sterner et al., 2014), while impacts that depend on CO_2 concentrations such as ocean acidification may begin to reverse. From an economic perspective, comparison of different climate forcers ideally reflects the ratio of marginal economic damages if used to determine the exchange ratio of different GHGs under multi–gas regulation (Tol et al., 2012; Deuber et al., 2013; Kolstad et al., 2014).

Emission reductions can interact with other dimensions of sustainable development (see Chapter 5). In particular, early action on some SLCFs (including actions that may warm the climate such as reducing SO_2 emissions) may have considerable societal co-benefits such as reduced air pollution and improved public health with associated economic benefits (OECD, 2016; Shindell et al., 2016). Valuation of broadly defined social costs attempts to account for many of these additional non–climate factors along with climate-related impacts (Shindell, 2015; Sarofim et al., 2017; Shindell et al., 2017). See Chapter 4, Section 4.3.6, for a discussions of mitigation options, noting that mitigation priorities for different climate forcers depend on multiple economic and social criteria that vary between sectors, regions and countries.



Cross Chapter Box 2, Figure 1: Implications of different approaches to calculating aggregate greenhouse gas emissions on a pathway to net zero (a) Aggregate emissions of well–mixed greenhouse gases (WMGHGs) under the RCP2.6 mitigation scenario expressed as CO_2–equivalent using GWP_{100} (blue); GTP_{100} (green) and GWP* (yellow). Aggregate WMGHG emissions appear to fall more rapidly if calculated using GWP* than using either GWP or GTP, primarily because GWP* equates falling methane emissions with negative CO_2 emissions, as only active CO_2 removal would have the same impact on radiative forcing and GMST as a reduction in methane emission rates. (b) Cumulative emissions of WMGHGs combined as in panel (a) (blue, green & yellow lines & left hand axis) and warming response to combined emissions (black dotted line & right hand axis, Millar et al. (2017a). The temperature response under ambitious mitigation is closely correlated with cumulative WMGHG emissions aggregated using GWP*, but with neither emission rate nor cumulative emissions if aggregated using GWP or GTP.

1.3 Impacts at 1.5°C and beyond

1.3.1 Definitions

Consistent with the AR5 (IPCC, 2014e) , 'impact' in this report refers to the effects of climate change on human and natural systems. Impacts may include the effects of changing hazards, such as the frequency and intensity of heat waves. 'Risk' refers to potential negative impacts of climate change where something of value is at stake, recognizing the diversity of values. Risks depend on hazards, exposure, vulnerability (including sensitivity and capacity to respond) and likelihood. Climate change risks can be managed through efforts to mitigate climate change forcers, adaptation of impacted systems and remedial measures (Section 1.4.1).

In the context of this report, *regional* impacts of *global* warming at 1.5°C and 2°C are assessed in Chapter 3. The '*warming experience at 1.5°C*' is that of regional climate change (temperature, rainfall, and other changes) at the time when global average temperatures, as defined in Section 1.2.1, reach 1.5°C above pre-industrial (the same principle applies to impacts at any other global mean temperature). Over the decade 2006-2015, many regions have experienced higher than average levels of warming and some are already now 1.5°C warmer with respect to the pre-industrial period (Figure 1.3). At a global warming of 1.5°C, some seasons will be substantially warmer than 1.5°C above pre–industrial (Seneviratne et al., 2016). Therefore, most regional impacts of a global mean warming of 1.5°C will be different from those of a regional warming by 1.5°C.

The impacts of 1.5°C global warming will vary in both space and time (Ebi et al., 2016). For many regions, an increase in global mean temperature by 1.5°C or 2°C implies substantial increases in the occurrence and/or intensity of some extreme events (Fischer and Knutti, 2015; Karmalkar and Bradley, 2017; King et al., 2017), resulting in different impacts (see Chapter 3). By comparing impacts at 1.5°C *vs.* those at 2°C, this report discusses the 'avoided impacts' by maintaining global temperature increase at or below 1.5°C as compared to 2°C, noting that these also depend on the pathway taken to 1.5°C (see Section 1.2.3 and Cross-Chapter Box 8 in Chapter 3 on 1.5°C warmer worlds). Many impacts take time to observe, and because of the warming trend, impacts over the past 20 years were associated with a level of human-induced warming that was, on average, 0.1–0.23°C colder than its present level, based on the AR5 estimate of the warming trend over this period (Section 1.2.1 and Kirtman et al., 2013). Attribution studies (e.g., van Oldenborgh et al., 2017) can address this bias, but informal estimates of 'recent impact experience' in a rapidly warming world necessarily understate the temperature-related impacts of the current level of warming.

1.3.2 Drivers of Impacts

Impacts of climate change are due to multiple environmental drivers besides rising temperatures, such as rising atmospheric CO_2, shifting rainfall patterns, rising sea levels, increasing ocean acidification, and extreme events, such as floods, droughts, and heat waves (IPCC, 2014e). For example, changes in rainfall affect the hydrological cycle and water availability (Schewe et al., 2014). Several impacts depend on atmospheric composition, for example, increasing atmospheric carbon dioxide levels leading to changes in plant productivity (Forkel et al., 2016), but also to ocean acidification (Hoegh-Guldberg et al., 2007). Other impacts are driven by changes in ocean heat content, for example, the destabilization of coastal ice-sheets and sea-level rise (Bindoff et al., 2007; Chen et al., 2017), whereas impacts due to heat waves depend directly on ambient air or ocean temperature (Matthews et al., 2017). Impacts can be direct, for example, coral bleaching due to ocean warming, and indirect, for example, reduced tourism due to coral bleaching. Indirect impacts can also arise from mitigation efforts such as changed agricultural management (Section 3.6.2) or remedial measures such as solar radiation modification (Section 4.3.8, Cross-Chapter Box 10 in Chapter 4).

Impacts may also be triggered by combinations of factors, including 'impact cascades' (Cramer et al., 2014) through secondary consequences of changed systems. Changes in agricultural water availability caused by upstream changes in glacier volume are a typical example. Recent studies also identify compound events (e.g., droughts and heat waves), that is, when impacts are induced by the combination of several climate events (AghaKouchak et al., 2014; Leonard et al., 2014; Martius et al., 2016; Zscheischler and Seneviratne, 2017).

There are now techniques to attribute impacts formally to anthropogenic global warming and associated rainfall changes (Rosenzweig et al., 2008; Cramer et al., 2014; Hansen et al., 2016), taking into account other drivers such as land use change (Oliver and Morecroft, 2014) and pollution (e.g., tropospheric ozone; Sitch et al., 2007). There are multiple lines of evidence that climate change has observable and often severely negative effects on people, especially where climate-sensitive biophysical conditions and socioeconomic / political constraints on adaptive capacities combine to create high vulnerabilities (IPCC, 2012c; World Bank, 2013; IPCC, 2014e). The character and severity of impacts depend not only on the hazards (e.g. changed climate averages and extremes) but also on the vulnerability (including sensitivities and adaptive capacities) of different communities and their exposure to climate threats. These impacts also affect a range of natural and human systems such as terrestrial, coastal and marine ecosystems and their services, agricultural production, infrastructure, the built environment, human health and other socio–economic systems (Rosenzweig et al., 2017).

Sensitivity to changing drivers varies markedly across systems and regions. Impacts of climate change on natural and managed ecosystems can imply loss or increase in growth, biomass or diversity at the level of species populations, interspecific relationships such as pollination, landscapes or entire biomes. Impacts occur in addition to the natural variation in growth, ecosystem dynamics, disturbance, succession and other processes, rendering attribution of impacts at lower levels of warming difficult in certain situations. The same magnitude of warming can be lethal during one phase of the life of an organism and irrelevant during another. Many ecosystems (notably forests, coral reefs and others) undergo long-term successional processes characterised by varying levels of resilience to environmental change over time. Organisms and ecosystems may adapt to environmental change to a certain degree, for example, through changes in physiology, ecosystem structure, species composition or evolution. Large-scale shifts in ecosystems may cause important feedbacks, for example, in terms of changing water and carbon fluxes through impacted ecosystems – these can amplify or dampen atmospheric change at regional to continental scale. For example, of particular concern, is the response of most of the world's forests and seagrass ecosystems, which play key roles as carbon sinks (Settele et al., 2014; Marbà et al., 2015).

Some ambitious efforts to constrain atmospheric greenhouse gas concentrations may themselves impact ecosystems. In particular, changes in land use, potentially required for massively enhanced production of biofuels (either as simple replacement of fossil fuels, or as part of Bioenergy with Carbon Capture and Storage, BECCS) impact all other land ecosystems through competition for land (e.g., Creutzig, 2016) (see Cross-Chapter Box 7 in Chapter 3, Section 3.6.2.1).

Human adaptive capacity to a 1.5°C warmer world varies markedly for individual sectors and across sectors such as water supply, public health, infrastructure, ecosystems and food supply. For example, density and risk exposure, infrastructure vulnerability and resilience, governance and institutional capacity all drive different impacts across a range of human settlement types (Dasgupta et al., 2014; Revi et al., 2014; Rosenzweig et al., 2018). Additionally, the adaptive capacity of communities and human settlements in both rural and urban areas, especially in highly populated regions, raises equity, social justice and sustainable development issues. Vulnerabilities due to gender, age, level of education and culture act as compounding factors (Arora-Jonsson, 2011; Cardona et al., 2012; Resurrección, 2013; Olsson et al., 2014; Vincent et al., 2014).

1.3.3 Uncertainty and non-linearity of impacts

Uncertainties in projections of future climate change and impacts come from a variety of different sources, including the assumptions made regarding future emission pathways (Moss et al., 2010), the inherent limitations and assumptions of the climate models used for the projections, including limitations in simulating regional climate variability (James et al., 2017), downscaling and bias-correction methods (Ekström et al., 2015), and in impact models (e.g., Asseng et al., 2013). The evolution of climate change also affects uncertainty with respect to impacts. For example, the impacts of overshooting 1.5°C and stabilization at a later stage, compared to stabilization at 1.5°C without overshoot may differ in magnitude (Schleussner et al., 2016).

AR5 IPCC (2013b) and World Bank (2013) underscored the non-linearity of risks and impacts as temperature rises from 2°C to 4°C of warming, particularly in relation to water availability, heat extremes, bleaching of coral reefs, and more. Recent studies (Schleussner et al., 2016; James et al., 2017; King et al., 2018) assess the impacts of 1.5°C versus 2°C warming, with the same message of non-linearity. The resilience of ecosystems, meaning their ability either to resist change or to recover after a disturbance, may change, and often decline, in a non-linear way. An example are reef ecosystems, with some studies suggesting that reefs will change, rather than disappear entirely, and particular species showing greater tolerance to coral bleaching than others (Pörtner et al., 2014). A key issue is therefore whether ecosystems such as coral reefs survive an overshoot scenario, and to what extent would they be able to recover after stabilization at 1.5°C or higher levels of warming (see Box 3.4).

1.4 Strengthening the global response

This section frames the implementation options, enabling conditions (discussed further in Cross-Chapter Box 3 on feasibility in this Chapter), capacities and types of knowledge and their availability (Blicharska et al., 2017) that can allow institutions, communities and societies to respond to the 1.5°C challenge in the context of sustainable development and the Sustainable Development Goals (SDGs). It also addresses other relevant international agreements such as the Sendai Framework for Disaster Risk Reduction. Equity and ethics are recognised as issues of importance in reducing vulnerability and eradicating poverty.

The connection between the enabling conditions for limiting global warming to 1.5°C and the ambitions of the SDGs are complex across scale and multifaceted (Chapter 5). Climate mitigation-adaptation linkages, including synergies and trade-offs, are important when considering opportunities and threats for sustainable development. The IPCC AR5 acknowledged that 'adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses' (Denton et al., 2014). Climate mitigation and adaptation measures and actions can reflect and enforce specific patterns of development and governance that differ amongst the world's regions (Gouldson et al., 2015; Termeer et al., 2017). The role of limited adaptation and mitigation capacity, limits to adaptation and mitigation, and conditions of mal-adaptation and mal-mitigation are assessed in this report (Chapters 4 and 5).

1.4.1 Classifying Response Options

Key broad categories of responses to the climate change problem are framed here. **Mitigation** refers to efforts to reduce or prevent the emission of greenhouse gases, or to enhance the absorption of gases already emitted, thus limiting the magnitude of future warming (IPCC, 2014c). Mitigation requires the use of new technologies, clean energy sources, reduced deforestation, improved sustainable agricultural methods, and changes in individual and collective behaviour. Many of these may provide substantial co-benefits for air quality, biodiversity and sustainable development. Mal-mitigation includes changes that could reduce emissions in the short-term but could lock in technology choices or practices that include significant trade-offs for effectiveness of future adaptation and other forms of mitigation (Chapters 2 and 4).

Carbon dioxide removal (CDR) or 'negative emissions' activities are considered a distinct type of mitigation. While most types of mitigation focus on reducing the amount of carbon dioxide or greenhouse gases emitted, CDR aims to reduce concentrations already in the atmosphere. Technologies for CDR are mostly in their infancy despite their importance to ambitious climate change mitigation pathways (Minx et al., 2017). Although some CDR activities such as reforestation and ecosystem restoration are well understood, the feasibility of massive-scale deployment of many CDR technologies remains an open question (IPCC, 2014d; Leung et al., 2014) (Chapters 2 and 4). Technologies for the active removal of other greenhouse gases, such as methane, are even less developed, and are briefly discussed in Chapter 4.

Climate change **adaptation** refers to the actions taken to manage the impacts of climate change (IPCC, 2014e). The aim is to reduce vulnerability and exposure to the harmful effects of climate change (e.g. sea–level rise, more intense extreme weather events or food insecurity). It also includes exploring the potential beneficial opportunities associated with climate change (for example, longer growing seasons or increased yields in some regions). Different adaptation-pathways can be undertaken. Adaptation can be incremental, or transformational, meaning fundamental attributes of the system are changed (Chapter 3 and 4). There can be limits to ecosystem-based adaptation or the ability of humans to adapt (Chapter 4). If there is no possibility for adaptive actions that can be applied to avoid an intolerable risk, these are referred to as hard adaptation limits, while soft adaptation limits are identified when there are currently no options to avoid intolerable risks, but they are theoretically possible (Chapter 3 and 4). While climate change is a global issue, impacts are experienced locally. Cities and municipalities are at the frontline of adaptation (Rosenzweig et al., 2018), focusing on reducing and managing disaster risks due to extreme and slow-onset weather and climate events, installing flood and drought early warning systems, and improving water storage and use (Chapters 3 and 4 and Cross-Chapter Box 12 in Chapter 5). Agricultural and rural areas, including often highly vulnerable remote and indigenous communities, also need to address climate-related risks by strengthening and making more resilient agricultural and other natural resource extraction systems.

Remedial measures are distinct from mitigation or adaptation, as the aim is to temporarily reduce or offset warming (IPCC, 2012b). One such measure is Solar Radiation Modification (SRM), also referred to as Solar Radiation Management in the literature, which involves deliberate changes to the albedo of the Earth system, with the net effect of increasing the amount of solar radiation reflected from the Earth to reduce the peak temperature from climate change (The Royal Society, 2009; Smith and Rasch, 2013; Schäfer et al., 2015). It should be noted that while some radiation modification measures, such as cirrus cloud thinning (Kristjánsson et al., 2016), aim at enhancing outgoing long-wave radiation, SRM is used in this report to refer to all direct interventions on the planetary radiation budget. This report does not use the term 'geo-engineering' because of inconsistencies in the literature, which uses this term to cover SRM, CDR or both, whereas this report explicitly differentiates between CDR and SRM. Large-scale SRM could potentially be used to supplement mitigation in overshoot scenarios to keep the global mean temperature below 1.5°C and temporarily reduce the severity of near-term impacts (e.g., MacMartin et al., 2018). The impacts of SRM (both biophysical and societal), costs, technical feasibility, governance and ethical issues associated need to be carefully considered (Schäfer et al., 2015; Section 4.3.8 and Cross-Chapter Box 10 in Chapter 4).

1.4.2 Governance, implementation and policies

A challenge in meeting the enabling conditions of 1.5°C warmer world is the governance capacity of institutions to develop, implement and evaluate the changes needed within diverse and highly interlinked global social-ecological systems (Busby, 2016) (Chapter 4). Policy arenas, governance structures and robust institutions are key enabling conditions for transformative climate action

(Chapter 4). It is through governance that justice, ethics and equity within the adaptation-mitigation-sustainable development nexus can be addressed (Stechow et al., 2016) (Chapter 5).

Governance capacity includes a wide range of activities and efforts needed by different actors to develop coordinated climate mitigation and adaptation strategies in the context of sustainable development taking into account equity, justice and poverty eradication. Significant governance challenges include the ability to incorporate multiple stakeholder perspectives in the decision-making process to reach meaningful and equitable decisions, interactions and coordination between different levels of government, and the capacity to raise financing and support for both technological and human resource development. For example, Lövbrand et al. (2017), argue that the voluntary pledges submitted by states and non-state actors to meet the conditions of the Paris Agreement will need to be more firmly coordinated, evaluated and upscaled.

Barriers for transitioning from climate change mitigation and adaptation planning to practical policy implementation include finance, information, technology, public attitudes, social values and practices (Whitmarsh et al., 2011; Corner and Clarke, 2017) and human resource constraints. Institutional capacity to deploy available knowledge and resources is also needed (Mimura et al., 2014). Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments with the support of national government and facilitating partnerships among public, civic, private sectors and higher education institutions (Leal Filho et al., 2018) can help in the implementation of identified response options (Chapter 4). Implementation challenges of 1.5ºC pathways are larger than for those that are consistent with limiting warming to well below 2ºC, particularly concerning scale and speed of the transition and the distributional impacts on ecosystems and socio-economic actors. Uncertainties in climate change at different scales and different capacities to respond combined with the complexities of coupled social and ecological systems point to a need for diverse and adaptive implementation options within and among different regions involving different actors. The large regional diversity between highly carbon-invested economies and emerging economies are important considerations for sustainable development and equity in pursuing efforts to limit warming to 1.5°C. Key sectors, including energy, food systems, health, and water supply, also are critical to understanding these connections.

Cross-Chapter Box 3: Framing feasibility: Key concepts and conditions for limiting global temperature increases to 1.5°C

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This Cross-Chapter Box describes the concept of feasibility in relation to efforts to limit global warming to 1.5°C in the context of sustainable development and efforts to eradicate poverty and draws from the understanding of feasibility emerging within the IPCC (IPCC, 2017). Feasibility can be assessed in different ways, and no single answer exists as to the question of whether it is feasible to limit warming to 1.5°C. This implies that an assessment of feasibility would go beyond a 'yes' or a 'no'. Rather, feasibility provides a frame to understand the different conditions and potential responses for implementing adaptation and mitigation pathways, and options compatible with a 1.5°C warmer world. This report assesses the overall feasibility of a 1.5°C world, and the feasibility of adaptation and mitigation options compatible with a 1.5°C warmer world in six dimensions:

Geophysical: What global emission pathways could be consistent with conditions of a 1.5°C warmer world? What are the physical potentials for adaptation?

Environmental-ecological: What are the ecosystem services and resources, including geological storage capacity and related rate of needed land use change, available to promote transformations, and to what extent are they compatible with enhanced resilience?
Technological: What technologies are available to support transformation?
Economic: What economic conditions could support transformation?
Socio-cultural: What conditions could support transformations in behaviour and lifestyles? To what extent are the transformations socially acceptable and consistent with equity?
Institutional: What institutional conditions are in place to support transformations, including multi-level governance, institutional capacity, and political support?

The report starts by assessing which mitigation pathways would lead to a 1.5°C world, which indicates that rapid and deep deviations from current emission pathways are necessary (Chapter 2). In the case of adaptation, an assessment of feasibility starts from an evaluation of the risks and impacts of climate change (Chapter 3). To mitigate and adapt to climate risks, system-wide technical, institutional and socio-economic transitions would be required, as well as the implementation of a range of specific mitigation and adaptation options. Chapter 4 applies various indicators categorised in these six dimensions to assess the feasibility of illustrative examples of relevant mitigation and adaptation options (Section 4.5.1). Such options and pathways have different effects on sustainable development, poverty eradication and adaptation capacity (Chapter 5).

The six feasibility dimensions interact in complex, and place-specific ways. Synergies and trade-offs may occur between the feasibility dimensions, and between specific mitigation and adaptation options (Section 4.5.4). The presence or absence of enabling conditions would affect the options that comprise feasibility pathways (Section 4.4), and can reduce trade-offs and amplify synergies between options.

Sustainable development, eradicating poverty and reducing inequalities are not only preconditions for feasible transformations, but the interplay between climate action (both mitigation and adaptation options) and the development patterns on which they apply may actually enhance the feasibility of particular options (see Chapter 5).

The connections between the feasibility dimensions can be specified across three types of effects (discussed below). Each of these dimensions presents challenges and opportunities in realizing conditions consistent with a 1.5°C warmer world.

Systemic effects: Conditions that have embedded within them system level functions that could include linear and non-linear connections and feedbacks. For example, the deployment of technology and large installations (e.g., renewable or low carbon energy mega–projects) depends upon economic conditions (costs, capacity to mobilize investments for R&D), social or cultural conditions (acceptability), and institutional conditions (political support; e.g., Sovacool et al., 2015). Case studies can demonstrate system level interactions and positive or negative feedback effects between the different conditions (Jacobson et al., 2015; Loftus et al., 2015). This suggests that each set of conditions and their interactions need to be considered to understand synergies, inequities and unintended consequences.

Dynamic effects: Conditions that are highly dynamic and vary over time, especially under potential conditions of overshoot or no overshoot. Some dimensions might be more time sensitive or sequential than others (i.e., if conditions are such that it is no longer geophysically feasible to avoid overshooting 1.5°C, the social and institutional feasibility of avoiding overshoot will be no longer relevant). Path dependencies, risks of legacy locks-ins related to existing infrastructures, and possibilities of acceleration permitted by cumulative effects like learning-by-doing driving dramatic costs decreases are all key features to be captured. The effects can play out over various time scales and thus require understanding the connections between near-term (meaning within the next several years to two decades) and their long-term implications (meaning over the next several decades) when assessing feasibility conditions.

Spatial effects: Conditions that are spatially variable and scale dependent, according to context-specific factors such as regional-scale environmental resource limits and endowment; economic wealth of local populations; social organisation, cultural beliefs, values and worldviews; spatial organisation, including conditions of urbanisation; and financial and institutional and governance capacity. This means that the conditions for achieving the global transformation required for a 1.5°C world will be heterogeneous and vary according to the specific context. On the other hand, the satisfaction of these conditions may depend upon global-scale drivers, such as international flows of finance, technologies or capacities. This points to the need for understanding feasibility to capture the interplay between the conditions at different scales.

With each effect, the interplay between different conditions influences the feasibility of both pathways (Chapter 2) and options (Chapter 4), which in turn affect the likelihood of limiting warming to 1.5°C. The complexity of these interplays triggers unavoidable uncertainties, requiring transformations that remain robust under a range of possible futures that limit warming to 1.5°C.

1.4.3 Transformation, transformation pathways, and transition: evaluating trade-offs and synergies between mitigation, adaptation and sustainable development goals

Embedded in the goal of limiting warming to 1.5°C is the opportunity for intentional societal transformation (see Box 1.1 on the Anthropocene). The form and process of transformation are varied and multifaceted (Pelling, 2011; O'Brien et al., 2012; O'Brien and Selboe, 2015; Pelling et al., 2015). Fundamental elements of 1.5°C-related transformation include a decoupling of economic growth from energy demand and CO_2 emissions, leap-frogging development to new and emerging low-carbon, zero-carbon and carbon-negative technologies, and synergistically linking climate mitigation and adaptation to global scale trends (e.g., global trade and urbanization) that will enhance the prospects for effective climate action, as well as enhanced poverty reduction and greater equity (Tschakert et al., 2013; Rogelj et al., 2015; Patterson et al., 2017) (Chapters 4 and 5). The connection between transformative climate action and sustainable development illustrates a complex coupling of systems that have important spatial and time scale lag effects and implications for process and procedural equity including intergenerational equity and for non-human species (Cross-Chapter Box 4 in this Chapter, Chapter 5). Adaptation and mitigation transition pathways highlight the importance of cultural norms and values, sector specific context, and proximate (i.e. occurrence of an extreme event) drivers that when acting together enhance the conditions for societal transformation (Solecki et al., 2017; Rosenzweig et al., 2018) (Chapters 4 and 5).

Diversity and flexibility in implementation choices exist for adaptation, mitigation (including carbon dioxide removal, CDR) and remedial measures (such as solar radiation modification, SRM), and a potential for trade-offs and synergies between these choices and sustainable development (IPCC, 2014f; Olsson et al., 2014). The responses chosen could act to synergistically enhance mitigation, adaptation and sustainable development or they may result in trade-offs which positively impact some aspects and negatively impact others. Climate change is expected to increase the likelihood of not achieving the Sustainable Development Goals (SDGs), while some strategies limiting warming towards 1.5°C are expected to significantly lower that risk and provide synergies for climate adaptation and mitigation (Chapter 5).

Dramatic transformations required to achieve the enabling conditions for a 1.5°C warmer world could impose trade-offs on dimensions of development (IPCC, 2014f; Olsson et al., 2014). Some choices of adaptation methods also could adversely impact development (Olsson et al., 2014).This report recognizes the potential for adverse impacts and focuses on finding the synergies between limiting warming, sustainable development, and eradicating poverty, thus highlighting pathways that do not constrain other goals, such as sustainable development and eradicating poverty.

The report is framed to address these multiple goals simultaneously and assesses the conditions to achieve a cost-effective and socially acceptable solution, rather than addressing these goals piecemeal (Stechow et al., 2016) (Section 4.5.4 and Chapter 5), although there may be different synergies and trade-offs between a 2°C (Stechow et al., 2016) and 1.5°C warmer world (Kainuma et al., 2017). Climate-resilient development pathways (see Cross-Chapter Box 12 in Chapter 5 and Glossary) are trajectories that strengthen sustainable development, including mitigating and adapting to climate change and efforts to eradicate poverty while promoting fair and cross-scalar resilience in a changing climate. They take into account dynamic livelihoods, the multiple dimensions of poverty, structural inequalities, and equity between and among poor and non-poor people (Olsson et al., 2014). Climate-resilient development pathways can be considered at different scales, including cities, rural areas, regions or at global level (Denton et al., 2014; Chapter 5).

Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals

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Sustainable development is most often defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987) and includes balancing social wellbeing, economic prosperity and environmental protection. The AR5 used this definition and linked it to climate change (Denton et al., 2014). The most significant step since AR5 is the adoption of the UN Sustainable Development Goals, and the emergence of literature that links them to climate (von Stechow et al., 2015; Wright et al., 2015; Epstein et al., 2017; Hammill and Price-Kelly, 2017; Kelman, 2017; Lofts et al., 2017; Maupin, 2017; Gomez-Echeverri, 2018).

In September 2015, the UN endorsed a universal agenda – 'Transforming our World: the 2030 Agenda for Sustainable Development' – which aims 'to take the bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path'. Based on a participatory process, the resolution in support of the 2030 agenda adopted 17 non-legally-binding Sustainable Development Goals (SDGs) and 169 targets to support people, prosperity, peace, partnerships and the planet (Kanie and Biermann, 2017).

The SDGs expanded efforts to reduce poverty and other deprivations under the UN Millennium Development Goals (MDGs). There were improvements under the MDGs between 1990 and 2015, including reducing overall poverty and hunger, reducing infant mortality, and improving access to drinking water (United Nations, 2015). However, greenhouse gas emissions increased by more than 50% from 1990 to 2015, and 1.6 billion people were still living in multidimensional poverty with persistent inequalities in 2015 (Alkire et al., 2015).

The SDGs raise the ambition for eliminating poverty, hunger, inequality and other societal problems while protecting the environment. They have been criticised: as too many and too complex, needing more realistic targets, overly focused on 2030 at the expense of longer term objectives, not embracing all aspects of sustainable development, and even contradicting each other (Horton, 2014; Death and Gabay, 2015; Biermann et al., 2017; Weber, 2017; Winkler and Satterthwaite, 2017).

Climate change is an integral influence on sustainable development, closely related to the economic, social and environmental dimensions of the SDGs. The IPCC has woven the concept of sustainable development into recent assessments, showing how climate change might undermine sustainable development, and the synergies between sustainable development and responses to climate change (Denton et al., 2014). Climate change is also explicit in the SDGs. SDG13 specifically requires 'urgent action to address climate change and its impacts'. The targets include strengthening resilience and adaptive capacity to climate-related hazards and natural disasters; integrating climate change measures into national policies, strategies and planning; and improving education, awareness-raising and human and institutional capacity.

Targets also include implementing the commitment undertaken by developed-country parties to the UNFCCC to the goal of mobilizing jointly $100 billion annually by 2020 and operationalizing the Green Climate Fund, as well as promoting mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and Small Island Developing States, including focusing on women, youth and local and marginalised communities. SDG13 also acknowledges that the United Nations Framework Convention on Climate Change (UNFCCC) is the primary international, intergovernmental forum for negotiating the global response to climate change.

Climate change is also mentioned in SDGs beyond SDG13, for example in goal targets 1.5, 2.4, 11.B, 12.8.1 related to poverty, hunger, cities and education respectively. The UNFCCC addresses other SDGs in commitments to 'control, reduce or prevent anthropogenic emissions of greenhouse gases […] in all relevant sectors, including the energy, transport, industry, agriculture, forestry and waste management sectors' (Art4, 1(c)) and to work towards 'the conservation and enhancement, as appropriate, of […] biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems' (Art4, 1(d)). This corresponds to SDGs that seek clean energy for all (Goal 7), sustainable industry (Goal 9) and cities (Goal 11) and the protection of life on land and below water (14 and 15).

The SDGs and UNFCCC also differ in their time horizons. The SDGs focus primarily on 2030 whereas the Paris Agreement sets out that 'Parties aim […] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'.

The IPCC decision to prepare this report of the impacts of 1.5°C and associated emission pathways explicitly asked for the assessment to be in the context of sustainable development and efforts to eradicate poverty. Chapter 1 frames the interaction between sustainable development, poverty eradication and ethics and equity. Chapter 2 assesses how risks and synergies of individual mitigation measures interact with1.5°C pathways within the context of the SDGs, and how these vary according to the mix of measures in alternative mitigation portfolios (Section 2.5). Chapter 3 examines the impacts of 1.5°C global warming on natural and human systems with comparison to 2°C and provides the basis for considering the interactions of climate change with sustainable development in Chapter 5. Chapter 4 analyses strategies for strengthening the response to climate change, many of which interact with sustainable development. Chapter 5 takes sustainable development, eradicating poverty and reducing inequalities as its focal point for the analysis of pathways to 1.5°C, and discusses explicitly the linkages between achieving SDGs while eradicating poverty and reducing inequality.

Cross-Chapter Box 4, Figure 1: Climate action is number 13 of the UN Sustainable Development Goals.

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development

This report employs information and data that are global in scope and include region-scale analysis. It also includes syntheses of municipal, sub-national, and national case studies. Global level statistics including physical and social science data are used, as well as detailed and illustrative case study material of particular conditions and contexts. The assessment provides the state of knowledge, including an assessment of confidence and uncertainty. The main timescale of the assessment is the 21st century and the time is separated into the near-, medium-, and long-term. Spatial and temporal contexts are illustrated throughout including: assessment tools that include dynamic projections of emission trajectories and the underlying energy and land transformation (Chapter 2); methods for assessing observed impacts and projected risks in natural and managed ecosystems and at 1.5°C and higher levels of warming in natural and managed ecosystems and human systems (Chapter 3); assess the feasibility of mitigation and adaptation options (Chapter 4); and linkages of the Shared Socioeconomic Pathways (SSPs) and Sustainable Development Goals (SDGs) (Cross-Chapter Boxes 1 and 4 in this Chapter, Chapter 2 and Chapter 5).

1.5.1 Knowledge sources and evidence used in the report

This report is based on a comprehensive assessment of documented evidence of the enabling conditions to pursuing efforts to limit the global average temperature to 1.5°C and adapt to this level of warming in the overarching context of the Anthropocene (Delanty and Mota, 2017). Two sources of evidence are used; peer-reviewed scientific literature and 'grey' literature in accordance with procedure on the use of literature in IPCC reports (IPCC, 2013a, Annex 2 to Appendix A), with the former being the dominant source. Grey literature is largely used on key issues not covered in peer-reviewed literature.

The peer-reviewed literature includes the following sources: 1) knowledge regarding the physical climate system and human-induced changes, associated impacts, vulnerabilities and adaptation options, established from work based on empirical evidence, simulations, modelling and scenarios, with emphasis on new information since the publication of the IPCC AR5 to the cut-off date for this report (15th of May 2018); 2) Humanities and social science theory and knowledge from actual human experiences of climate change risks and vulnerability in the context of the social-ecological systems, development, equity, justice, and the role of governance, and from indigenous knowledge systems; and 3) Mitigation pathways based on climate projections into the future.

The grey literature category extends to empirical observations, interviews, and reports from government, industry, research institutes, conference proceedings and international or other organisations. Incorporating knowledge from different sources, settings and information channels while building awareness at various levels will advance decision making and motivate implementation of context specific responses to 1.5°C warming (Somanathan et al., 2014). The assessment does not assess non–written evidence and does not use oral evidence, media reports, or newspaper publications. With important exceptions, such as China, published knowledge from the most vulnerable parts of the world to climate change is limited (Czerniewicz et al., 2017).

1.5.2 Assessment frameworks and methodologies

Climate models and associated simulations

The multiple sources of climate model information used in this assessment are provided in Chapter 2 (Section 2.2) and Chapter 3 (Section 3.2). Results from global simulations, which have also been assessed in previous IPCC reports and that are conducted as part of the World Climate Research Programme (WCRP) Coupled Models Inter-comparison Project (CMIP) are used. The IPCC AR4 and Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) reports were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. The simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g.; Knutti and Sedláček, 2012; Mueller and Seneviratne, 2014). In addition to the CMIP3 and CMIP5 experiments, results from coordinated regional climate model experiments (e.g.; the Coordinated Regional Climate Downscaling Experiment, CORDEX) have been assessed, which are available for different regions (Giorgi and Gutowski, 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al., 2014; Jacob and Solman, 2017) are newly available for 1.5°C projections. Recently, simulations from the 'Half a degree Additional warming, Prognosis and Projected Impacts' (HAPPI) multi-model experiment have been performed to specifically assess climate changes at 1.5°C vs 2°C global warming (Mitchell et al., 2016). The HAPPI protocol consists of coupled land-atmosphere initial condition ensemble simulations with prescribed sea surface temperatures (SSTs), sea-ice, GHG and aerosol concentrations, solar and volcanic activity that coincide with three forced climate states: present-day (2006–2015) (see section 1.2.1), and future (2091–2100) either with 1.5°C or 2°C global warming (prescribed by modified SSTs).

Detection and attribution of change in climate and impacted systems

Formalized scientific methods are available to detect and attribute impacts of greenhouse gas forcing on observed changes in climate (e.g. Hegerl et al., 2007; Seneviratne et al., 2012; Bindoff et al., 2013) and impacts of climate change on natural and human systems (e.g. Stone et al., 2013; Hansen and Cramer, 2015; Hansen et al., 2016). The reader is referred to these sources, as well as to the AR5 for more background on these methods.

Global climate warming has already reached approximately 1°C (see Section 1.2.1) relative to pre–industrial conditions, and thus 'climate at 1.5°C global warming' corresponds to approximately the addition of only half a degree of warming compared to the present day, comparable to the warming that has occurred since the 1970s (Bindoff et al., 2013). Methods used in the attribution of observed changes associate with this recent warming are therefore also applicable to assessments of future changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available.

Impacts of 1.5°C global warming can be assessed in part from regional and global climate changes that have already been detected and attributed to human influence (e.g., Schleussner et al., 2017) and are components of the climate system that are most responsive to current and projected future forcing. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments of climate change provided in Chapter 3 (Section 3.3) build upon joint assessments of a) changes that were observed and attributed to human influence up to the present, i.e. for 1°C global warming and b) projections for higher levels of warming (e.g., 2°C, 3°C or 4°C) to assess the changes at 1.5°C. Such assessments are for transient changes only (see Chapter 3, Section 3.3).

Besides quantitative detection and attribution methods, assessments can also be based on indigenous and local knowledge (see Chapter 4, Box 4.3). While climate observations may not be available to assess impacts from a scientific perspective, local community knowledge can also indicate actual impacts (Brinkman et al., 2016; Kabir et al., 2016). The challenge is that a community's perception of loss due to the impacts of climate change is an area that requires further research (Tschakert et al., 2017).

Costs and benefits analysis

Cost-benefit analyses are common tools used for decision-making, whereby the costs of impacts are compared to the benefits from different response actions (IPCC, 2014d, e). However, for the case of climate change, recognising the complex inter-linkages of the Anthropocene, cost-benefit analyses tools can be difficult to use because of disparate impacts versus costs and complex interconnectivity within the global social-ecological system (see Box 1.1 and Cross-Chapter Box 5 in Chapter 2). Some costs are relatively easily quantifiable in monetary terms but not all. Climate change impacts humans' lives and livelihoods, culture and values and whole ecosystem. It has unpredictable feedback loops and impacts on other regions, (IPCC, 2014e) giving rise to indirect, secondary, tertiary and opportunity costs that are typically extremely difficult to quantify. Monetary quantification is further complicated by the fact that costs and benefits can occur in different regions at very different times, possibly spanning centuries, while it is extremely difficult if not impossible to meaningfully estimate discount rates for future costs and benefits. Thus standard cost–benefit analyses become difficult to justify (IPCC, 2014e; Dietz et al., 2016) and are not used as an assessment tool in this report.

1.6 Confidence, uncertainty and risk

This report relies on the IPCC's uncertainty guidance provided in Mastrandrea et al. (2011), and sources given therein. Two metrics for qualifying key findings are used:

Confidence: Five qualifiers are used to express levels of confidence in key findings, ranging from *very low*, through *low*, *medium*, *high*, to *very high*. The assessment of confidence involves at least two dimensions, one being the type, quality, amount or internal consistency of individual lines of evidence, and the second being the level of agreement between different lines of evidence. Very high confidence findings must either be supported by a high level of agreement across multiple lines of mutually independent and individually robust lines of evidence or, if only a single line of evidence is available, by a very high level of understanding underlying that evidence. Findings of low or very low confidence are presented only if they address a topic of major concern.

Likelihood: A calibrated language scale is used to communicate assessed probabilities of outcomes, ranging from *exceptionally unlikely* (<1%), *extremely unlikely* (<5%), *very unlikely* (<10%), *unlikely* (<33%), *about as likely as not* (33–66%), *likely* (>66%), *very likely* (>90%), *extremely likely* (>95%)

to *virtually certain* (>99%). These terms are normally only applied to findings associated with high or very high confidence. Frequency of occurrence within a model ensemble does not correspond to actual assessed probability of outcome unless the ensemble is judged to capture and represent the full range of relevant uncertainties.

Three specific challenges arise in the treatment of uncertainty and risk in this report. First, the current state of the scientific literature on 1.5°C means that findings based on multiple lines of robust evidence for which quantitative probabilistic results can be expressed may be few, and not the most policy-relevant. Hence many key findings are expressed using confidence qualifiers alone.

Second, many of the most important findings of this report are conditional because they refer to ambitious mitigation scenarios. Conditional probabilities often depend strongly on how conditions are specified, such as whether temperature goals are met through early emission reductions, reliance on negative emissions, or through a low climate response. Whether a certain risk is deemed likely at 1.5°C may therefore depend strongly on how 1.5°C is specified, whereas a statement that a certain risk may be substantially higher at 2°C relative to 1.5°C may be much more robust.

Third, achieving ambitious mitigation goals will require active, goal-directed efforts aiming explicitly for specific outcomes and incorporating new information as it becomes available (Otto et al., 2015). This shifts the focus of uncertainty from the climate outcome itself to the level of mitigation effort that may be required to achieve it. Probabilistic statements about human decisions are always problematic, but in the context of robust decision-making, many near-term policies that are needed to keep open the option of achieving 1.5°C may be the same, regardless of the actual probability that the goal will be met (Knutti et al., 2015).

1.7 Storyline of the report

The storyline of this report (Figure 1.6) includes a set of interconnected components. The report consists of five chapters, a Technical Summary and a Summary for Policymakers. It also includes a set of boxes to elucidate specific or cross-cutting themes, as well as Frequently Asked Questions for each chapter and a Glossary.

At a time of unequivocal and rapid global warming, this report emerges from the long-term temperature goal of the Paris Agreement; strengthening the global response to the threat of climate change by pursuing efforts to limit warming to 1.5°C through reducing emissions to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases. The assessment focuses first, in Chapter 1, on how 1.5°C is defined and understood, what is the current level of warming to date, and the present trajectory of change. The framing presented in Chapter 1 provides the basis through which to understand the enabling conditions of a 1.5°C warmer world and connections to the SDGs, poverty eradication, and equity and ethics.

In Chapter 2, scenarios of a 1.5°C warmer world and the associated pathways are assessed. The pathways assessment builds upon the AR5 with a greater emphasis on sustainable development in mitigation pathways. All pathways begin now, and involve rapid and unprecedented societal transformation. An important framing device for this report is the recognition that choices that determine emissions pathways, whether ambitious mitigation or 'no policy' scenarios, do not occur independently of these other changes and are, in fact, highly interdependent.

Projected impacts that emerge in a 1.5°C warmer world and beyond are dominant narrative threads of the report and are assessed in Chapter 3. The chapter focuses on observed and attributable global and regional climate changes and impacts and vulnerabilities. The projected impacts have diverse and uneven spatial, temporal, and human, economic, and ecological system-level manifestations. Central to the assessment is the reporting of impacts at 1.5°C and 2°C, potential impacts avoided through limiting warming to 1.5°C, and, where possible, adaptation potential and limits to adaptive capacity.

Response options and associated enabling conditions emerge next, in Chapter 4. Attention is directed to exploring questions of adaptation and mitigation implementation and integration and transformation in a highly interdependent world, with consideration of synergies and trade-offs. Emission pathways, in particular, are broken down into policy options and instruments. The role of technological choices, institutional capacity and large-scale global scale trends like urbanization and changes in ecosystems are assessed.

Chapter 5 covers linkages between achieving the SDGs and a 1.5°C warmer world and turns toward identifying opportunities and challenges of transformation. This is assessed within a transition to climate-resilient development pathways, and connection between the evolution towards 1.5°C, associated impacts, and emission pathways. Positive and negative effects of adaptation and mitigation response measures and pathways for a 1.5°C warmer world are examined. Progress along these pathways involves inclusive processes, institutional integration, adequate finance and technology, and attention to issues of power, values, and inequalities to maximize the benefits of pursuing climate stabilisation at 1.5°C and the goals of sustainable development at multiple scales of human and natural systems from global, regional, national to local and community levels.

Figure 1.6: Schematic of report storyline.

Frequently Asked Questions

FAQ 1.1: Why are we talking about 1.5°C?

Summary: Climate change represents an urgent and potentially irreversible threat to human societies and the planet. In recognition of this, the overwhelming majority of countries around the world adopted the Paris Agreement in December 2015, the central aim of which includes pursuing efforts to limit global temperature rise to 1.5°C. In doing so, these countries, through the United Nations Framework Convention on Climate Change (UNFCCC) also invited the IPCC to provide a Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways.

At the 21st Conference of the Parties (COP21) in December 2015, 195 nations adopted the Paris Agreement[2]. The first instrument of its kind, the landmark agreement includes the aim to strengthen the global response to the threat of climate change by 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'.

The first UNFCCC document to mention a limit to global warming of 1.5°C was the Cancun Agreement, adopted at the sixteenth COP (COP16) in 2010. The Cancun Agreement established a process to periodically review the 'adequacy of the long-term global goal (LTGG) in the light of the ultimate objective of the Convention and the overall progress made towards achieving the LTGG, including a consideration of the implementation of the commitments under the Convention'. The definition of LTGG in the Cancun Agreement was 'to hold the increase in global average temperature below 2°C above pre-industrial levels'. The agreement also recognised the need to consider 'strengthening the long term global goal on the basis of the best available scientific knowledge… to a global average temperature rise of 1.5°C'.

Beginning in 2013 and ending at the COP21 in Paris in 2015, the first review period of the long term global goal largely consisted of the Structured Expert Dialogue (SED). This was a fact-finding, face-to-face exchange of views between invited experts and UNFCCC delegates. The final report of the SED[3] concluded that 'in some regions and vulnerable ecosystems, high risks are projected even for warming above 1.5°C'. The SED report also suggested that Parties would profit from restating the temperature limit of the long-term global goal as a 'defence line' or 'buffer zone', instead of a 'guardrail' up to which all would be safe, adding that this new understanding would 'probably also favour emission pathways that will limit warming to a range of temperatures below 2°C'. Specifically on strengthening the temperature limit of 2°C, the SED's key message was: 'While science on the 1.5°C warming limit is less robust, efforts should be made to push the defence line as low as possible'. The findings of the SED, in turn, fed into the draft decision adopted at COP21.

With the adoption of the Paris Agreement, the UNFCCC invited the IPCC to provide a Special Report in 2018 on 'the impacts of global warming of 1.5°C above pre–industrial levels and related global greenhouse gas emissions pathways'. The request was that the report, known as SR1.5, should not only assess what a 1.5°C warmer world would look like but also the different pathways by which global temperature rise could be limited to 1.5°C. In 2016, the IPCC accepted the invitation, adding that the Special Report would also look at these issues in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

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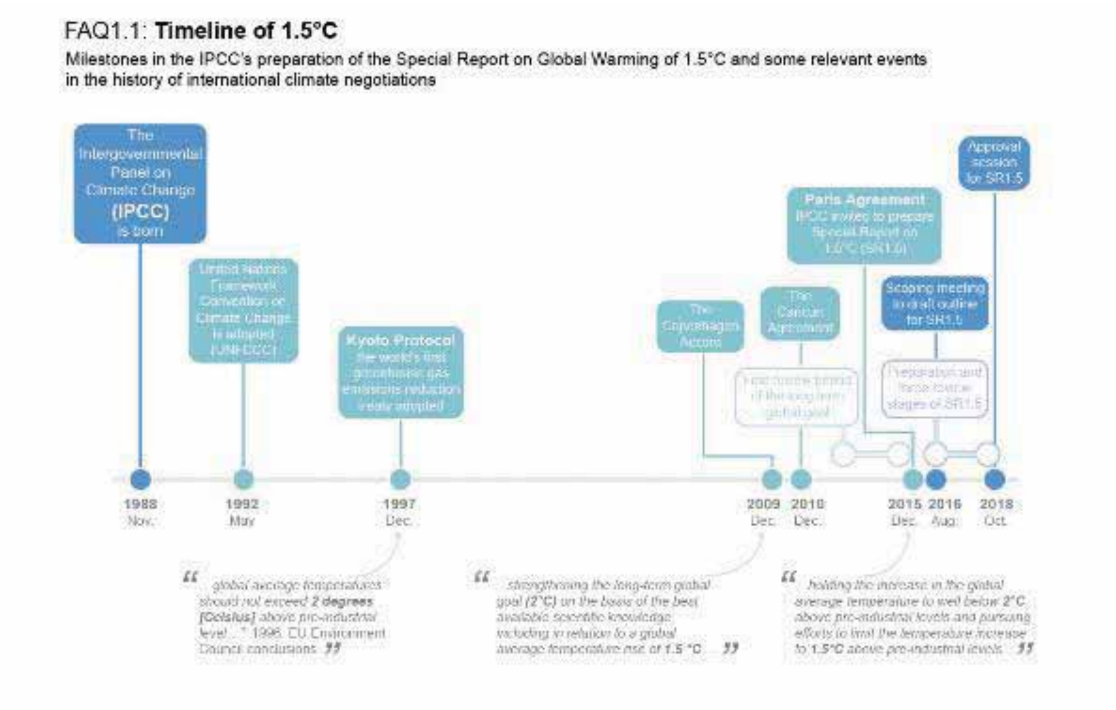
[2] FOOTNOTE: Paris Agreement FCCC/CP/2015/10/Add.1 https://unfccc.int/documents/9097

[3] FOOTNOTE: Structured Expert Dialogue (SED) final report FCCC/SB/2015/INF.1 https://unfccc.int/documents/8707

The combination of rising exposure to climate change and the fact that there is a limited capacity to adapt to its impacts amplifies the risks posed by warming of 1.5°C and 2°C. This is particularly true for developing and island countries in the tropics and other vulnerable countries and areas. The risks posed by global warming of 1.5°C are greater than for present day conditions but lower than at 2°C.



FAQ1.1, Figure 1: A timeline of notable dates in preparing the IPCC Special Report on Global Warming of 1.5°C (blue) embedded within processes and milestones of the United Nations Framework Convention on Climate Change (UNFCCC; grey), including events that may be relevant for discussion of temperature limits.

FAQ 1.2: How close are we to 1.5°C?

Summary: *Human-induced warming has already reached about 1°C above pre-industrial levels at the time of writing of this Special Report. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.12°C) compared pre-industrial times (1850–1900). If the current warming rate continues, the world would reach human–induced global warming of 1.5°C around 2040.*

Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. While the overall intention of strengthening the global response to climate change is clear, the Paris Agreement does not specify precisely what is meant by 'global average temperature', or what period in history should be considered 'pre-industrial'. To answer the question of how close are we to 1.5°C of warming, we need to first be clear about how both terms are defined in this Special Report.

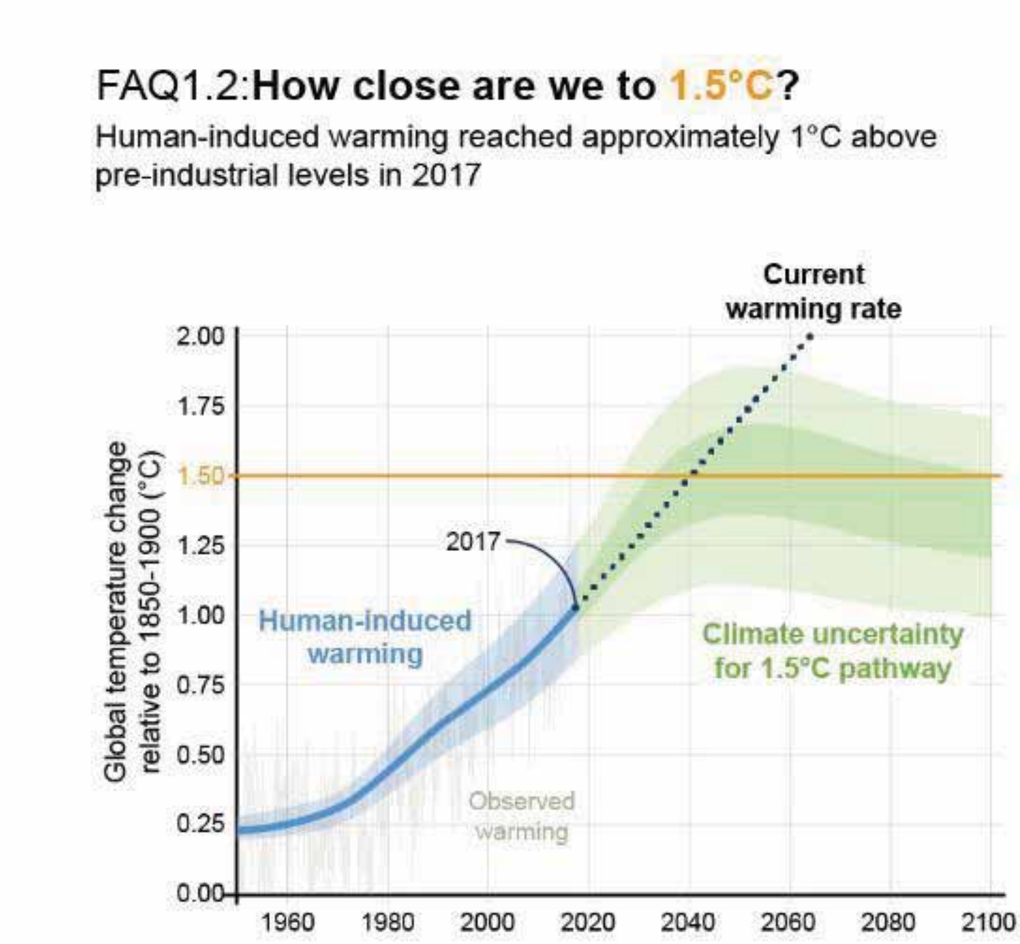
The choice of pre-industrial reference period, along with the method used to calculate global average temperature, can alter scientists' estimates of historical warming by a couple of tenths of a degree Celsius. Such differences become important in the context of a global temperature limit just half a degree above where we are now. But provided consistent definitions are used, they do not affect our understanding of how human activity is influencing the climate.

In principle, 'pre-industrial levels' could refer to any period of time before the start of the industrial revolution. But the number of direct temperature measurements decreases as we go back in time. Defining a 'pre-industrial' reference period is, therefore, a compromise between the reliability of the temperature information and how representative it is of truly pre-industrial conditions. Some pre-industrial periods are cooler than others for purely natural reasons. This could be because of spontaneous climate variability or the response of the climate to natural perturbations, such as volcanic eruptions and variations in the sun's activity. This IPCC Special Report on Global Warming of 1.5°C uses the reference period 1850 to 1900 to represent pre-industrial conditions. This is the earliest period with near-global observations and is the reference period used as an approximation of pre-industrial temperatures in the IPCC Fifth Assessment Report.

Once scientists have defined 'pre-industrial', the next step is to calculate the amount of warming at any given time relative to that reference period. In this report, warming is defined as the increase in the 30-year global average of combined temperature over land and at the ocean surface. The 30-year timespan accounts for the effect of natural variability, which can cause global temperatures to fluctuate from one year to the next. For example, 2015 and 2016 were both affected by a strong El Niño event, which amplified the underlying human-caused warming.

In the decade 2006–2015, warming reached 0.87°C (±0.12°C) relative to 1850–1900, predominantly due to human activity increasing the amount of greenhouse gases in the atmosphere. Given that global temperature is currently rising by 0.2°C (±0.1°C) per decade, human–induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, would reach 1.5°C around 2040.

While the change in global average temperature tells researchers about how the planet as a whole is changing, looking more closely at specific regions, countries and seasons reveals important details. Since the 1970s, most land regions have been warming faster than the global average, for example. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population live in regions that have already experienced warming in at least one season that is greater than 1.5°C above pre-industrial levels.



FAQ1.2, Figure 1: Human-induced warming reached approximately 1°C above pre-industrial levels in 2017. At the present rate, global temperatures would reach 1.5°C around 2040.

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Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development

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Executive Summary

This chapter assesses mitigation pathways consistent with limiting warming to 1.5°C above preindustrial levels. In doing so, it explores the following key questions: What role do CO_2 and non-CO_2 emissions play? {2.2, 2.3, 2.4, 2.6} To what extent do 1.5°C pathways involve overshooting and returning below 1.5°C during the 21st century? {2.2, 2.3} What are the implications for transitions in energy, land use and sustainable development? {2.3, 2.4, 2.5} How do policy frameworks affect the ability to limit warming to 1.5°C? {2.3, 2.5} What are the associated knowledge gaps? {2.6}

The assessed pathways describe integrated, quantitative evolutions of all emissions over the 21st century associated with global energy and land use, and the world economy. The assessment is contingent upon available integrated assessment literature and model assumptions, and is complemented by other studies with different scope, for example those focusing on individual sectors. In recent years, integrated mitigation studies have improved the characterizations of mitigation pathways. However, limitations remain, as climate damages, avoided impacts, or societal co-benefits of the modelled transformations remain largely unaccounted for, while concurrent rapid technological changes, behavioural aspects, and uncertainties about input data present continuous challenges. *(high confidence)* {2.1.3, 2.3, 2.5.1, 2.6, Technical Annex 2}

The chances of limiting warming to 1.5°C and the requirements for urgent action

1.5°C-consistent pathways can be identified under a range of assumptions about economic growth, technology developments and lifestyles. However, lack of global cooperation, lack of governance of the energy and land transformation, and growing resource-intensive consumption are key impediments for achieving 1.5°C-consistent pathways. Governance challenges have been related to scenarios with high inequality and high population growth in the 1.5°C pathway literature. {2.3.1, 2.3.2, 2.5}

Under emissions in line with current pledges under the Paris Agreement (known as Nationally-Determined Contributions or NDCs), global warming is expected to surpass 1.5°C, even if they are supplemented with very challenging increases in the scale and ambition of mitigation after 2030 (*high confidence*). This increased action would need to achieve net zero CO_2 emissions in less than 15 years. Even if this is achieved, temperatures remaining below 1.5°C would depend on the geophysical response being towards the low end of the currently-estimated uncertainty range. Transition challenges as well as identified trade-offs can be reduced if global emissions peak before 2030 and already achieve marked emissions reductions by 2030 compared to today.[1] {2.2, 2.3.5, Cross-Chapter Box 9 in Chapter 4}

Limiting warming to 1.5°C depends on greenhouse gas (GHG) emissions over the next decades, where lower GHG emissions in 2030 lead to a higher chance of peak warming being kept to 1.5°C (*high confidence*). Available pathways that aim for no or limited (0–0.2°C) overshoot of 1.5°C keep GHG emissions in 2030 to 25–30 $GtCO_2e\ yr^{-1}$ in 2030 (interquartile range). This contrasts with median estimates for current NDCs of 50–58 $GtCO_2e\ yr^{-1}$ in 2030. Pathways that aim for limiting warming to 1.5°C by 2100 after a temporary temperature overshoot rely on large-scale deployment of Carbon Dioxide Removal (CDR) measures, which are uncertain and entail clear risks. {2.2, 2.3.3, 2.3.5, 2.5.3, Cross-Chapter Boxes 6 in Chapter 3 and 9 in Chapter 4, 4.3.7}

Limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane (*high confidence*). Such mitigation pathways are characterized by energy-demand reductions, decarbonisation of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and some form of CDR with carbon storage on land or sequestration in geological reservoirs. Low energy demand and low demand for land- and GHG-intensive consumption goods facilitate limiting warming to as close as possible to 1.5°C. {2.2.2, 2.3.1, 2.3.5, 2.5.1, Cross-Chapter Box 9 in Chapter 4}.

[1] FOOTNOTE: Kyoto-GHG emissions in this statement are aggregated with GWP-100 values of the IPCC Second Assessment Report.

In comparison to a 2°C limit, required transformations to limit warming to 1.5°C are qualitatively similar but more pronounced and rapid over the next decades (*high confidence*). 1.5°C implies very ambitious, internationally cooperative policy environments that transform both supply and demand *(high confidence)*. {2.3, 2.4, 2.5}

Policies reflecting a high price on emissions are necessary in models to achieve cost-effective 1.5°C-consistent pathways *(high confidence)*. Other things being equal, modelling suggests the price of emissions for limiting warming to 1.5°C being about three four times higher compared to 2°C, with large variations across models and socioeconomic assumptions. A price on carbon can be imposed directly by carbon pricing or implicitly by regulatory policies. Other policy instruments, like technology policies or performance standards, can complement carbon pricing in specific areas. {2.5.1, 2.5.2, 4.4.5}

Limiting warming to 1.5°C requires a marked shift in investment patterns *(limited evidence, high agreement)*. Investments in low-carbon energy technologies and energy efficiency would need to approximately double in the next 20 years, while investment in fossil-fuel extraction and conversion decrease by about a quarter. Uncertainties and strategic mitigation portfolio choices affect the magnitude and focus of required investments. {2.5.2}

Future emissions in 1.5°C-consistent pathways

Mitigation requirements can be quantified using carbon budget approaches that relate cumulative CO_2 emissions to global-mean temperature increase. Robust physical understanding underpins this relationship, but uncertainties become increasingly relevant as a specific temperature limit is approached. These uncertainties relate to the transient climate response to cumulative carbon emissions (TCRE), non-CO_2 emissions, radiative forcing and response, potential additional Earth-system feedbacks (such as permafrost thawing), and historical emissions and temperature. {2.2.2, 2.6.1}

Cumulative CO_2 emissions are kept within a budget by reducing global annual CO_2 emissions to net-zero. This assessment suggests a remaining budget for limiting warming to 1.5°C with a two-thirds chance of about 550 $GtCO_2$, and of about 750 $GtCO_2$ for an even chance (*medium confidence*). The remaining carbon budget is defined here as cumulative CO_2 emissions from the start of 2018 until the time of net-zero global emissions. Remaining budgets applicable to 2100, would approximately be 100 $GtCO_2$ lower than this to account for permafrost thawing and potential methane release from wetlands in the future. These estimates come with an additional geophysical uncertainty of at least ±50%, related to non-CO_2 response and TCRE distribution. In addition, they can vary by ±250 $GtCO_2$ depending on non-CO_2 mitigation strategies as found in available pathways. {2.2.2, 2.6.1}

Staying within a remaining carbon budget of 750 $GtCO_2$ implies that CO_2 emissions reach carbon neutrality in about 35 years, reduced to 25 years for a 550 $GtCO_2$ remaining carbon budget (*high confidence*). The ±50% geophysical uncertainty range surrounding a carbon budget translates into a variation of this timing of carbon neutrality of roughly ±15–20 years. If emissions do not start declining in the next decade, the point of carbon neutrality would need to be reached at least two decades earlier to remain within the same carbon budget. {2.2.2, 2.3.5}

Non-CO_2 emissions contribute to peak warming and thus affect the remaining carbon budget. The evolution of methane and sulphur dioxide emissions strongly influences the chances of limiting warming to 1.5°C. In the near-term, a weakening of aerosol cooling would add to future warming, but can be tempered by reductions in methane emissions *(high confidence)*. Uncertainty in radiative forcing estimates (particularly aerosol) affects carbon budgets and the certainty of pathway categorizations. Some non-CO_2 forcers are emitted alongside CO_2, particularly in the energy and transport sectors, and can be largely addressed through CO_2 mitigation. Others require specific measures, for example to target agricultural N_2O and CH_4, some sources of black carbon, or hydrofluorocarbons *(high confidence).* In many cases, non-CO_2 emissions reductions are similar in 2°C pathways, indicating reductions near their assumed maximum potential by integrated assessment models. Emissions of N_2O and NH_3 increase in some pathways with strongly increased bioenergy demand. {2.2.2, 2.3.1, 2.4.2, 2.5.3}

The role of Carbon-Dioxide Removal (CDR)

All analysed 1.5°C-consistent pathways use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net-negative emissions that allow temperature to return to 1.5°C following an overshoot (*high confidence*). The longer the delay in reducing CO_2 emissions towards zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net-negative emissions after mid-century to return warming to 1.5°C (*high confidence*). The faster reduction of net CO_2 emissions in 1.5°C- compared to 2°C-consistent pathways is predominantly achieved by measures that result in less CO_2 being produced and emitted, and only to a smaller degree through additional CDR. Limitations on the speed, scale, and societal acceptability of CDR deployment also limit the conceivable extent of temperature overshoot. Limits to our understanding of how the carbon cycle responds to net negative emissions increase the uncertainty about the effectiveness of CDR to decline temperatures after a peak. {2.2, 2.3, 2.6, 4.3.7}

CDR deployed at scale is unproven and reliance on such technology is a major risk in the ability to limit warming to 1.5°C. CDR is needed less in pathways with particularly strong emphasis on energy efficiency and low demand. The scale and type of CDR deployment varies widely across 1.5°C-consistent pathways, with different consequences for achieving sustainable development objectives (*high confidence*). Some pathways rely more on bioenergy with carbon capture and storage (BECCS), while others rely more on afforestation, which are the two CDR methods most often included in integrated pathways. Trade-offs with other sustainability objectives occur predominantly through increased land, energy, water and investment demand. Bioenergy use is substantial in 1.5°C-consistent pathways with or without BECCS due to its multiple roles in decarbonizing energy use. {2.3.1, 2.5.3, 2.6, 4.3.7}

Properties of energy transitions in 1.5°C-consistent pathways

The share of primary energy from renewables increases while coal usage decreases across 1.5°C-consistent pathways *(high confidence)*. By 2050, renewables (including bioenergy, hydro, wind and solar, with direct-equivalence method) supply a share of 49–67% (interquartile range) of primary energy in 1.5°C-consistent pathways; while the share from coal decreases to 1–7% (interquartile range), with a large fraction of this coal use combined with Carbon Capture and Storage (CCS). From 2020 to 2050 the primary energy supplied by oil declines in most pathways (–32 to –74% interquartile range). Natural gas changes by –13% to –60% (interquartile range), but some pathways show a marked increase albeit with widespread deployment of CCS. The overall deployment of CCS varies widely across 1.5°C-consistent pathways with cumulative CO_2 stored through 2050 ranging from zero up to 460 $GtCO_2$ (minimum-maximum range), of which zero up to 190 $GtCO_2$ stored from biomass. Primary energy supplied by bioenergy ranges from 40–310 EJ yr^{-1} in 2050 (minimum-maximum range), and nuclear from 3–120 EJ/yr (minimum-maximum range). These ranges reflect both uncertainties in technological development and strategic mitigation portfolio choices. {2.4.2}

1.5°C-consistent pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use *(high confidence)*. By 2050, the carbon intensity of electricity decreases to -92 to +11 gCO_2/MJ (minimum-maximum range) from about 140 gCO_2/MJ in 2020, and electricity covers 34–71% (minimum-maximum range) of final energy across 1.5°C-consistent pathways from about 20% in 2020. By 2050, the share of electricity supplied by renewables increases to 36–97% (minimum-maximum range) across 1.5°C-consistent pathways. Pathways with higher chances of holding warming to below 1.5°C generally show a faster decline in the carbon intensity of electricity by 2030 than pathways that temporarily overshoot 1.5°C. {2.4.1, 2.4.2, 2.4.3}

Demand-side mitigation and behavioural changes

Demand-side measures are key elements of 1.5°C-consistent pathways. Lifestyle choices lowering energy demand and the land- and GHG-intensity of food consumption can further support achievement of 1.5°C-consistent pathways (*high confidence*). By 2030 and 2050, all end-use sectors (including building, transport, and industry) show marked energy demand reductions in modelled 1.5°C-consistent pathways, comparable and beyond those projected in 2°C-consistent pathways. Sectorial models support the scale of these reductions. {2.3.4, 2.4.3}

Links between 1.5°C-consistent pathways and sustainable development

Choices about mitigation portfolios for limiting warming to 1.5°C can positively or negatively impact the achievement of other societal objectives, such as sustainable development (*high confidence*). In particular, demand-side and efficiency measures, and lifestyle choices that limit energy, resource, and GHG-intensive food demand support sustainable development *(medium confidence)*. Limiting warming to 1.5°C can be achieved synergistically with poverty alleviation and improved energy security and can provide large public health benefits through improved air quality, preventing millions of premature deaths. However, specific mitigation measures, such as bioenergy, may result in trade-offs that require consideration. {2.5.1, 2.5.2, 2.5.3}

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

This chapter assesses the literature on mitigation pathways to limit or return global mean warming to 1.5°C (relative to the preindustrial base period 1850–1900). Key questions addressed are: What types of mitigation pathways have been developed that could be consistent with 1.5°C? What changes in emissions, energy and land use do they entail? What do they imply for climate policy and implementation, and what impacts do they have on sustainable development? In terms of feasibility (see Cross-Chapter Box 3 in Chapter 1), this chapter focuses on geophysical dimensions and technological and economic enabling factors, with social and institutional dimensions as well as additional aspects of technical feasibility covered in Chapter 4.

Mitigation pathways are typically designed to reach a pre-defined climate target alone. Minimization of mitigation expenditures, but not climate-related damages or sustainable development impacts, is often the basis for these pathways to the desired climate target (see Cross-Chapter Box 5 in Chapter 2 for additional discussion). However, there are interactions between mitigation and multiple other sustainable development goals (see Sections 1.1 and 5.4) that provide both challenges and opportunities for climate action. Hence there are substantial efforts to evaluate the effects of the various mitigation pathways on sustainable development, focusing in particular on aspects for which Integrated Assessment Models (IAMs) provide relevant information (e.g., land-use changes and biodiversity, food security, and air quality). More broadly, there are efforts to incorporate climate change mitigation as one of multiple objectives that in general reflect societal concerns more completely and could potentially provide benefits at lower costs than simultaneous single objective policies (e.g., Clarke et al., 2014). For example, with carefully selected policies, universal energy access can be achieved while simultaneously reducing air pollution and mitigating climate change (McCollum et al., 2011; Riahi et al., 2012; IEA, 2017d). This chapter thus presents both the pathways and an initial discussion of their context within sustainable development objectives (Section 2.5), with the latter along with equity and ethical issues discussed in more detail in Chapter 5.

As described in Cross-Chapter Box 1 in Chapter 1, scenarios are comprehensive, plausible, integrated descriptions of possible futures based on specified, internally consistent underlying assumptions, with pathways often used to describe the clear temporal evolution of specific scenario aspects or goal-oriented scenarios. We include both these usages of 'pathways' here.

2.1.1 Mitigation pathways consistent with 1.5°C

Emissions scenarios need to cover all sectors and regions over the 21st century to be associated with a climate change projection out to 2100. Assumptions regarding future trends in population, consumption of goods and services (including food), economic growth, behaviour, technology, policies and institutions are all required to generate scenarios (Section 2.3.1). These societal choices must then be linked to the drivers of climate change, including emissions of well-mixed greenhouse gases and aerosol and ozone precursors, and land-use and land-cover changes. Deliberate solar radiation modification is not included in these scenarios (see Cross-Chapter Box 10 in Chapter 4).

Plausible developments need to be anticipated in many facets of the key sectors of energy and land use. Within energy, these consider energy resources like biofuels, energy supply and conversion technologies, energy consumption, and supply and end-use efficiency. Within land use, agricultural productivity, food demand, terrestrial carbon management, and biofuel production are all considered. Climate policies are also considered, including carbon pricing and technology policies such as research and development funding and subsidies. The scenarios incorporate regional differentiation in sectoral and policy development. The climate changes resulting from such scenarios are derived using models that typically incorporate physical understanding of the carbon-cycle and climate response derived from complex geophysical models evaluated against observations (Sections 2.2 and 2.6).

The temperature response to a given emission pathway is uncertain and therefore quantified in terms of a probabilistic outcome. Chapter 1 assesses the climate objectives of the Paris agreement in terms of human-induced warming, thus excluding potential impacts of natural forcing such as volcanic eruptions or solar output changes or unforced internal variability. Temperature responses in this chapter are assessed using simple geophysically-based models that evaluate the anthropogenic component of future temperature change and do not incorporate internal natural variations and are thus fit for purpose in the context of this assessment (Section 2.2.1). Hence a scenario that is consistent with 1.5°C may in fact lead to either a higher or lower temperature change, but within quantified and generally well-understood bounds (see also Section 1.2.3). Consistency with avoiding a human-induced temperature change limit must therefore also be defined probabilistically, with likelihood values selected based on risk avoidance preferences. Responses beyond global mean temperature are not typically evaluated in such models and are assessed in Chapter 3.

2.1.2 The Use of Scenarios

Variations in scenario assumptions and design define to a large degree which questions can be addressed with a specific scenario set, for example, the exploration of implications of delayed climate mitigation action. In this assessment, the following classes of 1.5°C – and 2°C – consistent scenarios are of particular interest to the topics addressed in this chapter: (a) scenarios with the same climate target over the 21st century but varying socio-economic assumptions (Sections 2.3 and 2.4); (b) pairs of scenarios with similar socio-economic assumptions but with forcing targets aimed at 1.5°C and 2°C (Section 2.3); (c) scenarios that follow the Nationally Determined Contributions or NDCs[2] until 2030 with much more stringent mitigation action thereafter (Section 2.3.5).

Characteristics of these pathways such as emissions reduction rates, time of peaking, and low-carbon energy deployment rates can be assessed as being consistent with 1.5°C. However, they cannot be assessed as ‘requirements’ for 1.5°C, unless a targeted analysis is available that specifically asked whether there could be pathways without the characteristics in question. AR5 already assessed such targeted analyses, for example asking which technologies are important to keep open the possibility to limit warming to 2°C (Clarke et al., 2014). By now, several such targeted analyses are also available for questions related to 1.5°C (Luderer et al., 2013; Rogelj et al., 2013b; Bauer et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). This assessment distinguishes between consistent and the much stronger concept of required characteristics of 1.5°C pathways wherever possible.

Ultimately, society will adjust as new information becomes available and technical learning progresses, and these adjustments can be in either direction. Earlier scenario studies have shown, however, that deeper emissions reductions in the near term hedge against the uncertainty of both climate response and future technology availability (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014). Not knowing what adaptations might be put in place in the future, and due to limited studies, this chapter examines prospective rather than iteratively adaptive mitigation pathways (Cross-Chapter Box 1 in Chapter 1). Societal choices illustrated by scenarios may also influence what futures are envisioned as possible or desirable and hence whether those come into being (Beck and Mahony, 2017).

2.1.3 New scenario information since AR5

In this chapter, we extend the AR5 mitigation pathway assessment based on new scenario literature. Updates in understanding of climate sensitivity, transient climate response, radiative forcing, and the cumulative carbon budget consistent with 1.5°C are discussed in Sections 2.2.

Mitigation pathways developed with detailed process-based IAMs covering all sectors and regions over the 21st century describe an internally consistent and calibrated (to historical trends) way to get from current developments to meeting long-term climate targets like 1.5°C (Clarke et al., 2014). The overwhelming majority of available 1.5°C pathways were generated by such IAMs and these can be directly linked to climate outcomes and their consistency with the 1.5°C goal evaluated. The AR5 similarly relied upon such studies, which were mainly discussed in Chapter 6 of Working Group III (WGIII) (Clarke et al., 2014).

Since the AR5, several new integrated multi-model studies have appeared in the literature that explore

[2] FOOTNOTE: Current pledges include those from the US although they have stated their intention to withdraw in the future.

specific characteristics of scenarios more stringent than the lowest scenario category assessed in AR5 that was assessed to limit warming below 2°C with greater that 66% likelihood (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Su et al., 2017; Liu et al., 2017; Marcucci et al., 2017; Bauer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018). Those scenarios explore 1.5°C-consistent pathways from multiple perspectives (see Annex 2.A.3), examining sensitivity to assumptions regarding:

- socio-economic drivers and developments including energy and food demand as, for example, characterized by the shared socio-economic pathways (SSPs; Cross-Chapter Box 1 in Chapter 1)
- near-term climate policies describing different levels of strengthening the NDCs
- the use of bioenergy and availability and desirability of carbon-dioxide-removal (CDR) technologies

A large number of these scenarios were collected in a scenario database established for the assessment of this Special Report (Annex 2.A.3). Mitigation pathways were classified by four factors: consistency with a temperature limit (as defined by Chapter 1), whether they temporarily overshoot that limit, the extent of this potential overshoot, and the likelihood of falling within these bounds. Specifically, they were put into classes that either kept surface temperatures below a given threshold throughout the 21st century or returned to a value below 1.5°C at some point before 2100 after temporarily exceeding that level earlier, referred to as an overshoot (OS). Both groups were further separated based on the probability of being below the threshold and the degree of overshoot, respectively (Table 2.1). Pathways are uniquely classified, with 1.5°C-related classes given higher priority than 2°C classes in cases where a pathway would be applicable to either class.

The probability assessment used in the scenario classification are based on simulations using two reduced complexity carbon-cycle, atmospheric composition and climate models: the 'Model for the Assessment of Greenhouse Gas Induced Climate Change' (MAGICC) (Meinshausen et al., 2011a), and the 'Finite Amplitude Impulse Response' (FAIRv1.3) model (Smith et al., 2018). For the purpose of this report, and to facilitate comparison with AR5, the range of the key carbon-cycle and climate parameters for MAGICC and its setup are identical to those used in AR5 WGIII (Clarke et al., 2014). For each mitigation pathway, MAGICC and FAIR simulations provide probabilistic estimates of atmospheric concentrations, radiative forcing and global temperature outcomes until 2100. However, the classification uses MAGICC probabilities directly for traceability with AR5 and since this model is more established in the literature. Nevertheless, the overall uncertainty assessment is based on results from both models, which are considered in the context of the latest radiative forcing estimates and observed temperatures (Etminan et al., 2016; Smith et al., 2018) (Section 2.2 and Annex 2.A.1). The comparison of these lines of evidence shows *high agreement* in the relative temperature response of pathways, with *medium agreement* on the precise absolute magnitude of warming, introducing a level of imprecision in these attributes. Consideration of the combined evidence here leads to *medium confidence* in the overall geophysical characteristics of the pathways reported here.

Table 2.1: Classification of pathways this chapter draws upon along with the number of available pathways in each class. The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Annex 2.A.4.

Pathway Group	*Pathway Class*	*Pathway selection criteria and description*	*Number of scenarios*	*Number of scenarios*
1.5°C or 1.5°C-consistent	*Below-1.5°C*	*Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50-66% likelihood**	*9*	*90*
	1.5°C-low-OS	*Pathways limiting median warming to below 1.5°C in 2100 and with a 50-67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways*	*44*	
	1.5°C-high-OS	*Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways*	*37*	
2°C or 2°C-consistent	*Lower-2°C*	*Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood*	*74*	*132*
	Higher-2°C	*Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50-66% likelihood*	*58*	

** No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.*

In addition to the characteristics of the above-mentioned classes, four illustrative pathway archetypes have been selected and are used throughout this chapter to highlight specific features of and variations across 1.5°C pathways. These are chosen in particular to illustrate the spectrum of CO_2 emissions reduction patterns consistent with 1.5°C, ranging from very rapid and deep near-term decreases facilitated by efficiency and demand-side measures that lead to limited CDR requirements to relatively slower but still rapid emissions reductions that lead to a temperature overshoot and necessitate large CDR deployment later in the century (Section 2.3).

2.1.4 Utility of integrated assessment models (IAMs) in the context of this report

IAMs lie at the basis of the assessment of mitigation pathways in this chapter as much of the quantitative global scenario literature is derived with such models. IAMs combine insights from various disciplines in a single framework resulting in a dynamic description of the coupled energy-economy-land-climate system that cover the largest sources of anthropogenic greenhouse gas (GHG) emissions from different sectors. Many of the IAMs that contributed mitigation scenarios to this assessment include a process-based description of the land system in addition to the energy system (e.g., Popp et al., 2017), and several have been extended to cover air pollutants (Rao et al., 2017) and water use (Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016). Such integrated pathways hence allow the exploration of the whole-system transformation, as well as the interactions, synergies, and trade-offs between sectors, and increasing with questions beyond climate mitigation (von Stechow et al., 2015). The models do not, however, fully account for all constraints that could affect realization of pathways (see Chapter 4).

Section 2.3 assesses the overall characteristics of 1.5°C pathways based on fully integrated pathways, while Sections 2.4 and 2.5 describe underlying sectorial transformations, including insights from sector-specific assessment models and pathways that are not derived from IAMs. Such models provide detail in their domain of application and make exogenous assumptions about cross-sectoral or global factors. They often focus on a specific sector, such as the energy (Bruckner et al., 2014; IEA, 2017a; Jacobson, 2017; OECD/IEA and IRENA, 2017), buildings (Lucon et al., 2014) or transport (Sims et al., 2014) sector, or a specific country or region (Giannakidis et al., 2018). Sector-specific pathways are assessed in relation to integrated pathways because they cannot be directly linked to 1.5°C by themselves if they do not extend to 2100 or do not include all GHGs or aerosols from all sectors.

AR5 found sectorial 2°C decarbonisation strategies from IAMs to be consistent with sector-specific studies (Clarke et al., 2014). A growing body of literature on 100%-renewable energy scenarios has emerged (e.g., see Creutzig et al., 2017; Jacobson et al., 2017), which goes beyond the wide range of IAM projections of renewable energy shares in 1.5°C and 2°C pathways. While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, leading to higher renewable energy deployments in many cases (Luderer et al., 2017; Pietzcker et al., 2017), none of the IAM projections identify 100% renewable energy solutions for the global energy system as part of cost-effective mitigation pathways (Section 2.4.2). Bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in 2030 than realized in selected 2°C pathways from IAMs (UNEP 2017), indicating the possibility to strengthen sectorial decarbonisation strategies until 2030 beyond the integrated 1.5°C pathways assessed in this chapter (Luderer et al., 2018).

Detailed process-based IAMs are a diverse set of models ranging from partial equilibrium energy-land models to computable general equilibrium models of the global economy, from myopic to perfect foresight models, and from models with to models without endogenous technological change (Annex 2.A.2). The IAMs used in this chapter have limited to no coverage of climate impacts. They typically use GHG pricing mechanisms to induce emissions reductions and associated changes in energy and land uses consistent with the imposed climate goal. The scenarios generated by these models are defined by the choice of climate goals and assumptions about near-term climate policy developments. They are also shaped by assumptions about mitigation potentials and technologies as well as baseline developments such as, for example, those represented by different Shared Socioeconomic Pathways (SSPs), especially those pertaining to energy and food demand (Riahi et al., 2017). See Section 2.3.1 for discussion of these assumptions. Since the AR5, the scenario literature has greatly expanded the exploration of these dimensions. This includes low demand scenarios (Grubler et al., 2018; van Vuuren et al., 2018), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2018), scenarios with restricted availability of CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b; van Vuuren et al., 2018), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2018b) and scenario variations across the Shared Socioeconomic Pathways (Riahi et al., 2017; Rogelj et al., 2018). IAM results depend upon multiple underlying assumptions, for example the extent to which global markets and economies are assumed to operate frictionless and policies are cost-optimised, assumptions about technological progress and availability and costs of mitigation and CDR measures, assumptions about underlying socio-economic developments and future energy, food and materials demand, and assumptions about the geographic and temporal pattern of future regulatory and carbon pricing policies (see Annex 2.A.2 for additional discussion on IAMs and their limitations).

2.2 Geophysical relationships and constraints

Emissions pathways can be characterised by various geophysical characteristics such as radiative forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b), atmospheric concentrations (van Vuuren et al., 2007, 2011a; Clarke et al., 2014) or associated temperature outcomes (Meinshausen et al., 2009; Rogelj et al., 2011; Luderer et al., 2013). These attributes can be used to derive geophysical relationships for specific pathway classes, such as cumulative CO_2 emissions compatible with a specific level of warming also known as 'carbon budgets' (Meinshausen et al., 2009; Rogelj et al., 2011; Stocker et al., 2013; Friedlingstein et al., 2014a), the consistent contributions of non-CO_2 GHGs and aerosols to the remaining carbon budget (Bowerman et al., 2011; Rogelj et al., 2015a, 2016b) or to temperature outcomes (Lamarque et al., 2011; Bowerman et al., 2013; Rogelj et al., 2014b). This section assesses geophysical relationships for both CO_2 and non-CO_2 emissions.

2.2.1 Geophysical characteristics of mitigation pathways

This section employs the pathway classification introduced in Section 2.1, with geophysical characteristics derived from simulations with the MAGICC reduced-complexity carbon-cycle and climate model and supported by simulations with the FAIR reduced-complexity model (Section 2.1). Within a specific category and between models, there remains a large degree of variance. Most pathways exhibit a temperature overshoot which has been highlighted in several studies focusing on stringent mitigation pathways (Huntingford and Lowe, 2007; Wigley et al., 2007; Nohara et al., 2015; Rogelj et al., 2015d; Zickfeld and Herrington, 2015; Schleussner et al., 2016; Xu and Ramanathan, 2017). Only very few of the scenarios collected in the database for this report hold the average future warming projected by MAGICC below 1.5°C during the entire 21st century (Table 2.1, Figure 2.1). Most 1.5°C-consistent pathways available in the database overshoot 1.5°C around mid-century before peaking and then reducing temperatures so as to return below that level in 2100. However, because of numerous geophysical uncertainties and model dependencies (Section 2.2.1.1, Annex 2.A.1), absolute temperature characteristics of the various pathway categories are more difficult to distinguish than relative features (Figure 2.1, Annex 2.A.1) and actual probabilities of overshoot are imprecise. However, all lines of evidence available for temperature projections indicate a probability greater than 50% of overshooting 1.5°C by mid-century in all but the most stringent pathways currently available (Annex 2.A.1, 2.A.4).

Most 1.5°C-consistent pathways exhibit a peak in temperature by mid-century whereas 2°C-consistent pathways generally peak after 2050 (Annex 2.A.4). The peak in median temperature in the various pathway categories occurs about ten years before reaching net zero CO_2 emissions due to strongly reduced annual CO_2 emissions and deep reductions in CH_4 emissions (Section 2.3.3). The two reduced-complexity climate models used in this assessment suggest that virtually all available 1.5°C-consistent pathways peak and decline global-mean temperature rise, but with varying rates of temperature decline after the peak (Figure 2.1). The estimated decadal rates of temperature change by the end of the century are smaller than the amplitude of the climate variability as assessed in AR5 (1σ of about ±0.1°C), which hence complicates the detection of a global peak and decline of warming in observations on timescales of on to two decades (Bindoff et al., 2013). In comparison, many pathways limiting warming to 2°C or higher by 2100 still have noticeable increasing trends at the end of the century, and thus imply continued warming.

By 2100, the difference between 1.5°C- and 2°C-consistent pathways becomes clearer compared to mid-century, and not only for the temperature response (Figure 2.1) but also for atmospheric CO_2 concentrations. In 2100, the median CO_2 concentration in 1.5°C-consistent pathways is below 2016 levels (Le Quéré et al., 2018), whereas it remains higher by about 5-10% compared to 2016 in the 2°C-consistent pathways.

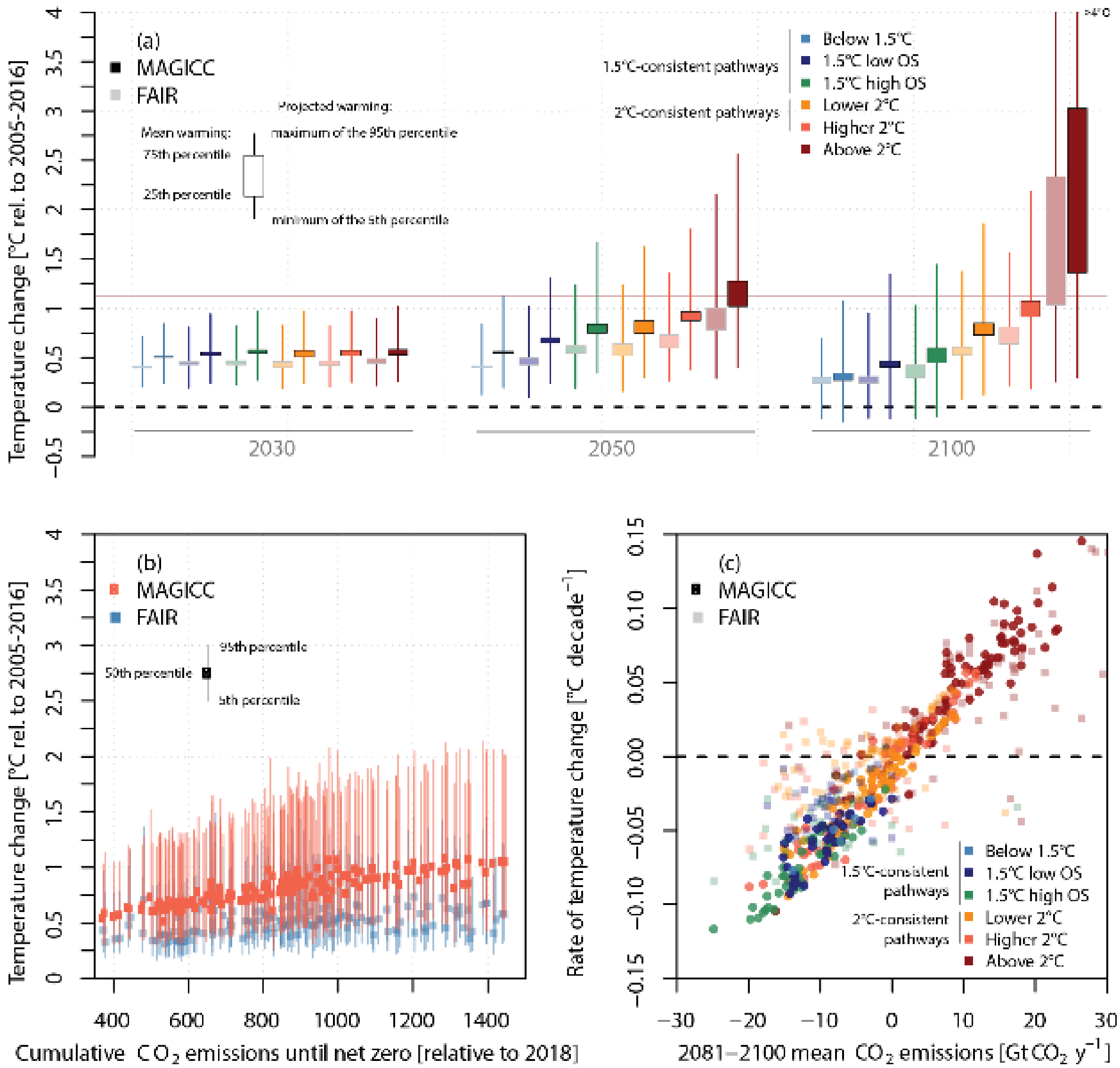

Figure 2.1: Pathways classification overview. (a) Average global-mean temperature increase relative to 2010 as projected by FAIR and MAGICC in 2030, 2050 and 2100; (b) response of peak warming to cumulative CO_2 emissions until net zero by MAGICC (red) and FAIR (blue); (c) decadal rate of average global-mean temperature change from 2081 to 2100 as a function of the annual CO_2 emissions averaged over the same period as given by FAIR (transparent squares) and MAGICC (filled circles). In panel (a), horizontal lines at 0.63°C and 1.13°C are indicative of the 1.5°C and 2°C warming thresholds with the respect to 1850–1900, taking into account the assessed historical warming of 0.87°C ±0.12°C between the 1850–1900 and 2006–2015 periods (Section 1.2.1). In panel (a), vertical lines illustrate both the physical and the scenario uncertainty as captured by MAGICC and FAIR and show the minimal warming of the 5th percentile of projected warming and the maximal warming of the 95th percentile of projected warming per scenario class. Boxes show the interquartile range of mean warming across scenarios, and thus represent scenario uncertainty only.

2.2.1.1 *Geophysical uncertainties: non-CO2 forcing agents*

Impacts of non-CO_2 climate forcers on temperature outcomes are particularly important when evaluating stringent mitigation pathways (Weyant et al., 2006; Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Samset et al., 2018). However, many uncertainties affect the role of non-CO_2 climate forcers in stringent mitigation pathways.

A first uncertainty arises from the magnitude of the radiative forcing attributed to non-CO_2 climate forcers. Figure 2.2 illustrates how, for one representative 1.5°C-consistent pathway (SSP2-1.9) (Fricko et al., 2017; Rogelj et al., 2018), the effective radiative forcings as estimated by MAGICC and FAIR can differ (see Annex 2.A.1 for further details). This large spread in non-CO_2 effective radiative forcings leads to considerable uncertainty in the predicted temperature response. This uncertainty ultimately affects the assessed temperature outcomes for pathway classes used in this chapter (Section 2.1) and also affects the carbon budget (Section 2.2.2). Figure 2.2 highlights the important role of methane emissions reduction in this scenario in agreement with the recent literature focussing on stringent mitigation pathways (Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Stohl et al., 2015; Collins et al., 2018).

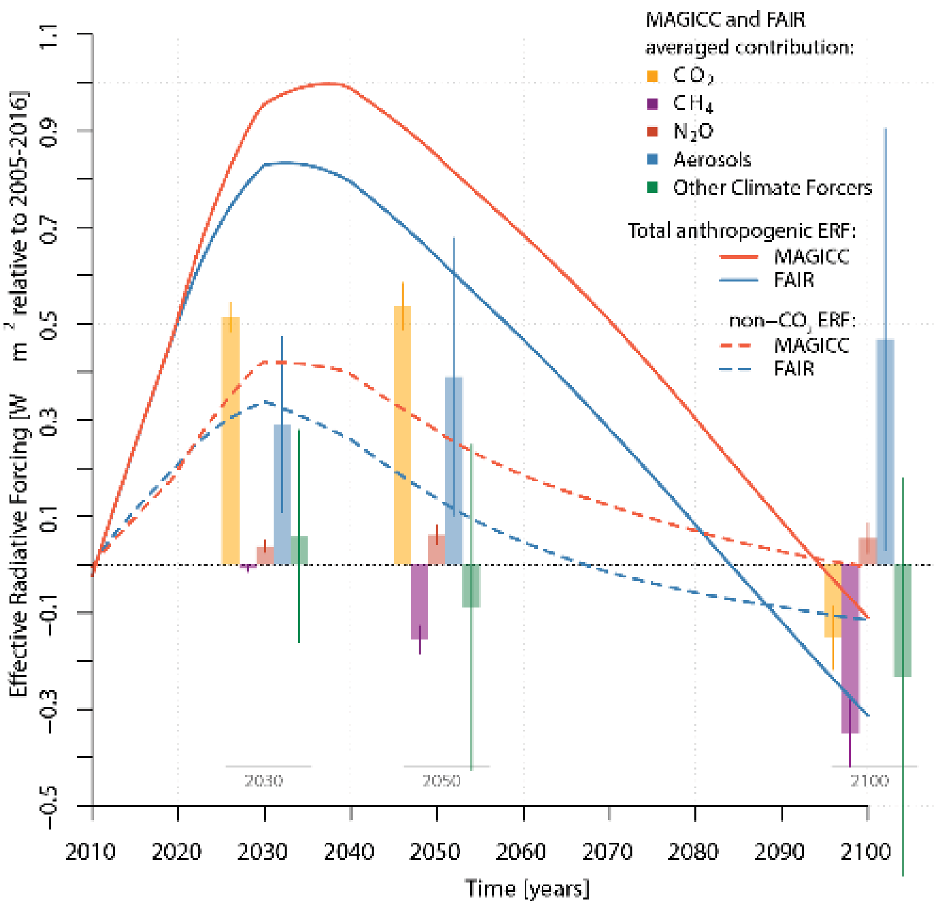

Figure 2.2: Changes and uncertainties in effective radiative forcings (ERF) for one 1.5°C-consistent pathway (SSP2-19) as estimated by MAGICC and FAIR. Solid and dashed lines are indicative of the effective radiative forcing for CO_2 and non-CO_2 agents as represented by MAGICC (red) and FAIR (blue) relative to 2010, respectively. Vertical bars show the mean radiative forcing as predicted by MAGICC and FAIR of relevant non-CO_2 agents for year 2030, 2050 and 2100. The vertical lines give the uncertainty (1σ) of the ERFs for the represented species.

For mitigation pathways that aim at halting and reversing radiative forcing increase during this century, the aerosol radiative forcing is a considerable source of uncertainty (Figure 2.2) (Samset et al., 2018; Smith et al., 2018). Indeed, reductions in SO_2 (and NO_x) emissions largely associated with fossil-fuel burning are expected to reduce the cooling effects of both aerosol radiative interactions and aerosol cloud interactions, leading to warming (Myhre et al., 2013; Samset et al., 2018). A multi-model analysis (Myhre et al., 2017) and a study based on observational constraints (Malavelle et al., 2017) largely support the AR5 best estimate and uncertainty range of aerosol forcing. The partitioning of total aerosol radiative forcing between aerosol precursor emissions is important (Ghan et al., 2013; Jones et al., 2018; Smith et al., 2018) as this affects the estimate of the mitigation potential from different sectors that have aerosol precursor emission sources. The total aerosol effective radiative forcing change in stringent mitigation pathways is expected to be dominated by the effects from the phase-out of SO_2, although the magnitude of this aerosol-warming effect depends on how much of the present-day aerosol cooling is attributable to SO_2, particularly the cooling associated with aerosol-cloud interaction (Figure 2.2). Regional differences in the linearity of aerosol-cloud interaction (Carslaw et al., 2013; Kretzschmar et al., 2017) make it difficult to separate the role of individual precursors. Precursors that are not fully mitigated will continue to affect the Earth system. If, for example, the role of nitrate aerosol cooling is at the strongest end of the assessed IPCC AR5 uncertainty range, future temperature increases may be more modest if ammonia emissions continue to rise (Hauglustaine et al., 2014).

Figure 2.2 shows that there are substantial differences in the evolution of estimated effective radiative forcing of non-CO_2 forcers between MAGICC and FAIR. These forcing differences result in MAGICC simulating a larger warming trend in the near term compared to both the FAIR model and the recent observed trends of 0.2°C per decade reported in Chapter 1 (Figure 2.1, Annex 2.A.1, Section 1.2.1.3). The aerosol effective forcing is stronger in MAGICC compared to either FAIR or the AR5 best estimate, though it is still well within the AR5 uncertainty range (Annex 2.A.1.1). A recent revision (Etminan et al., 2016) increases the methane forcing by 25%. This revision is used in the FAIR but not in the AR5 setup of MAGICC that is applied here. Other structural differences exist in how the two models relate emissions to concentrations that contribute to differences in forcing (see Annex 2.A.1.1).

Non-CO_2 climate forcers exhibit a greater geographical variation in radiative forcings than CO_2, which lead to important uncertainties in the temperature response (Myhre et al., 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al., 2014). It is also important to note that geographical patterns of temperature change and other climate responses, especially those related to precipitation, depend significantly on the forcing mechanism (Myhre et al., 2013; Shindell et al., 2015; Marvel et al., 2016; Samset et al., 2016) (see also Section 3.6.2.2).

2.2.1.2 *Geophysical uncertainties: climate and Earth-system feedbacks*

Climate sensitivity uncertainty impacts future projections as well as carbon-budget estimates (Schneider et al., 2017). AR5 assessed the equilibrium climate sensitivity (ECS) to be *likely* in the 1.5–4.5°C range, *extremely unlikely* less than 1°C and *very unlikely* greater than 6°C. The lower bound of this estimate is lower than the range of CMIP5 models (Collins et al., 2013). The evidence for the 1.5°C lower bound on ECS in AR5 was based on analysis of energy-budget changes over the historical period. Work since AR5 has suggested that the climate sensitivity inferred from such changes has been lower than the 2xCO_2 climate sensitivity for known reasons (Forster, 2016; Gregory and Andrews, 2016; Rugenstein et al., 2016; Armour, 2017; Ceppi and Gregory, 2017; Knutti et al., 2017; Proistosescu and Huybers, 2017). Both a revised interpretation of historical estimates and other lines of evidence based on analysis of climate models with the best representation of today's climate (Sherwood et al., 2014; Zhai et al., 2015; Tan et al., 2016; Brown and Caldeira, 2017; Knutti et al., 2017) suggest that the lower bound of ECS could be revised upwards which would decrease the chances of limiting warming below 1.5°C in assessed pathways. However, such a reassessment has been challenged (Lewis and Curry, 2018), albeit from a single line of evidence. Nevertheless, it is premature to make a major revision to the lower bound. The evidence for a possible revision of the upper bound on ECS is less clear with cases argued from different lines of evidence for both decreasing (Lewis and Curry, 2015, 2018; Cox et al., 2018) and increasing (Brown and Caldeira, 2017) the bound presented in the literature. The tools used in this chapter employ ECS ranges consistent with the AR5 assessment. The MAGICC ECS distribution has not been selected to explicitly reflect this but is nevertheless consistent (Rogelj et al., 2014a). The FAIR model used here to estimate carbon budgets explicitly constructs log-normal distributions of ECS and transient climate response based on a multi parameter fit to the AR5 assessed ranges of climate sensitivity and individual historic effective radiative forcings (Smith et al., 2018) (Annex 2.A.1.1).

Several feedbacks of the Earth system, involving the carbon cycle, non-CO_2 GHGs and/or aerosols, may also impact the future dynamics of the coupled carbon-climate system's response to anthropogenic emissions. These feedbacks are caused by the effects of nutrient limitation (Duce et al., 2008; Mahowald et al., 2017), ozone exposure (de Vries et al., 2017), fire emissions (Narayan et al., 2007) and changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2017). Among these Earth-system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies. Combined evidence from both models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and field studies (like Schädel et al., 2014; Schuur et al., 2015) shows *high agreement* that permafrost thawing will release both CO_2 and CH_4 as the Earth warms, amplifying global warming. This thawing could also release N_2O (Voigt et al., 2017a, 2017b). Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 $GtCO_2$ in Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014). Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO_2 (Schädel et al., 2016), while the amount of CH_4 released by permafrost thawing is estimated to be much smaller than that CO_2. Cumulative CH_4 release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015) with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

The reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO_2 Earth-system feedbacks, although the MAGICC model has a permafrost module that can be enabled. Taking the current climate and Earth-system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways (Section 2.2.2).

2.2.2 The remaining 1.5°C carbon budget

2.2.2.1 Carbon budget estimates

Since the AR5, several approaches have been proposed to estimate carbon budgets compatible with 1.5°C or 2°C. Most of these approaches indirectly rely on the approximate linear relationship between peak global-mean temperature and cumulative emissions of carbon (the transient climate response to cumulative emissions of carbon, TCRE (Collins et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b) whereas others base their estimates on equilibrium climate sensitivity (Schneider et al., 2017). The AR5 employed two approaches to determine carbon budgets. Working Group I (WGI) computed carbon budgets from 2011 onwards for various levels of warming relative to the 1861–1880 period using RCP8.5 (Meinshausen et al., 2011b; Stocker et al., 2013) whereas WGIII estimated their budgets from a set of available pathways that were assessed to have a >50% probability to exceed 1.5°C by mid-century, and return to 1.5°C or below in 2100 with greater than 66% probability (Clarke et al., 2014). These differences made AR5 WGI and WGIII carbon budgets difficult to compare as they are calculated over different time periods, derived from a different sets of multi-gas and aerosol emission scenarios and use different concepts of carbon budgets (exceedance for WGI, avoidance for WGIII) (Rogelj et al., 2016b; Matthews et al., 2017).

Carbon budgets can be derived from CO_2-only experiments as well as from multi-gas and aerosol scenarios. Some published estimates of carbon budgets compatible with 1.5°C or 2°C refer to budgets for CO_2-induced warming only, and hence do not take into account the contribution of non-CO_2 climate forcers (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009; IPCC, 2013a). However, because the projected changes in non-CO_2 climate forcers tend to amplify future warming, CO_2-only carbon budgets overestimate the total net cumulative carbon emissions compatible with 1.5°C or 2°C (Friedlingstein et al., 2014a; Rogelj et al., 2016b; Matthews et al., 2017; Mengis et al., 2018; Tokarska et al., 2018).

Since the AR5, many estimates of the remaining carbon budget for 1.5°C have been published (Friedlingstein et al., 2014a; MacDougall et al., 2015; Peters, 2016; Rogelj et al., 2016b; Matthews et al., 2017; Millar et al., 2017; Goodwin et al., 2018b; Kriegler et al., 2018a; Lowe and Bernie, 2018; Mengis et al., 2018; Millar and Friedlingstein, 2018; Rogelj et al., 2018; Schurer et al., 2018; Séférian et al., 2018;

Tokarska et al., 2018; Tokarska and Gillett, 2018). These estimates cover a wide range as a result of differences in the models used, and of methodological choices, as well as physical uncertainties. Some estimates are exclusively model-based while others are based on observations or on a combination of both. Remaining carbon budgets limiting warming below 1.5°C or 2°C that are derived from Earth-system models of intermediate complexity (MacDougall et al., 2015; Goodwin et al., 2018a), IAMs (Luderer et al., 2018; Rogelj et al., 2018), or based on Earth-system model results (Lowe and Bernie, 2018; Séférian et al., 2018; Tokarska and Gillett, 2018) give remaining carbon budgets of the same order of magnitude than the IPCC AR5 Synthesis Report (SYR) estimates (IPCC, 2014a). This is unsurprising as similar sets of models were used for the AR5 (IPCC, 2013b). The range of variation across models stems mainly from either the inclusion or exclusion of specific Earth-system feedbacks (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) or different budget definitions (Rogelj et al., 2018).

In contrast to the model-only estimates discussed above and employed in the AR5, this report additionally uses observations to inform its evaluation of the remaining carbon budget. Table 2.2 shows that the assessed range of remaining carbon budgets consistent with 1.5°C or 2°C is larger than the AR5 SYR estimate and is part way towards estimates constrained by recent observations (Millar et al., 2017; Goodwin et al., 2018a; Tokarska and Gillett, 2018). Figure 2.3 illustrates that the change since AR5 is, in very large part, due to the application of a more recent observed baseline to the historic temperature change and cumulative emissions; here adopting the baseline period of 2006-2015 (see Section 1.2.1). AR5 SYR Figures SPM.10 and 2.3 already illustrated the discrepancy between models and observations, but did not apply this as a correction to the carbon budget because they were being used to illustrate the overall linear relationship between warming and cumulative carbon emissions in the CMIP5 models since 1870, and were not specifically designed to quantify residual carbon budgets relative to the present for ambitious temperature goals. The AR5 SYR estimate was also dependent on a subset of Earth-system models illustrated in Figure 2.3 of this report. Although, as outlined below and in Table 2.2, considerably uncertainties remain, there is *high agreement* across various lines of evidence assessed in this report that the remaining carbon budget for 1.5°C or 2°C would be larger than the estimates at the time of the AR5. However, the overall remaining budget for 2100 is assessed to be smaller than that derived from the recent observational-informed estimates, as Earth-system feedbacks such as permafrost thawing reduce the budget applicable to centennial scales (see Section 2.2.2.2).

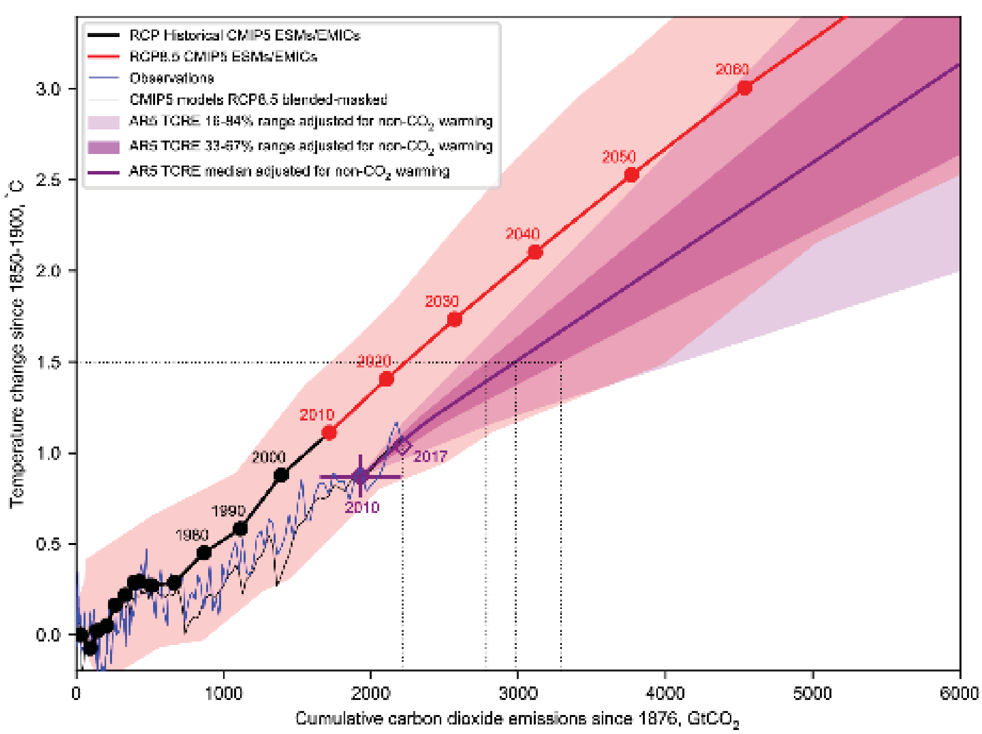

Figure 2.3: Temperature changes from 1850-1900 versus cumulative CO_2 emissions since 1st January 1876. Solid lines with dots reproduce the temperature response to cumulative CO_2 emissions plus non-CO_2 forcers as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a

particular year, unlike in WGI AR5 Fig. SPM10 where each point relates to the mean over the previous decade. The AR5 data was derived from available Earth-system models and Earth-system models of Intermediate Complexity for the historic observations (black) and RCP 8.5 scenario (red) and the red shaded plume shows the uncertainty range across the models as presented in the AR5. The purple shaded plume and the line are indicative of the temperature response to cumulative CO_2 emissions and non-CO_2 warming adopted in this report. The non-CO_2 warming contribution is averaged from the MAGICC and FAIR models and the purple shaded range assumes the AR5 WGI TCRE distribution (Annex 2.A.1.2). The 2010 observations of temperature anomaly (0.87°C based on 2006-2015 mean compared to 1850-1900, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 $GtCO_2$ (Le Quéré et al., 2018) is shown as a filled purple diamond. 2017 values based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 $GtCO_2$ (Version 1.3 accessed 22 May 2018) and a temperature anomaly of 1.04°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond. The thin blue line shows annual observations, with CO_2 emissions from (Le Quéré et al., 2018) and temperatures from the average of datasets in Chapter 1, Figure 1.2. The thin black line shows the CMIP5 models blended-masked estimates with CO_2 emissions also from (Le Quéré et al., 2018). Dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2. Note these remaining budgets exclude possible Earth-system feedbacks that could reduce the budget, such as CO_2 and CH_4 release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

2.2.2.2 *CO_2 and non-CO_2 contributions to the remaining carbon budget*

A remaining carbon budget can be estimated from calculating the amount of CO_2 emissions consistent, given a certain value of TCRE, with an allowable additional amount of warming. Here, the allowable warming is the 1.5°C warming threshold minus the current warming taken as the 2006-2015 average, with a further amount removed to account for the estimated non-CO_2 temperature contribution to the remaining warming (Peters, 2016; Rogelj et al., 2016b). This assessment uses the TCRE range from AR5 WGI (Collins et al., 2013) supported by estimates of non-CO_2 contributions that are based on published methods and integrated pathways (Friedlingstein et al., 2014a; Allen et al., 2016, 2018; Peters, 2016; Smith et al., 2018). Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see Annex 2.A.1.2 for details). With an assessed historical warming of 0.87°C ±0.12°C from 1850–1900 to 2006–2015 (Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a global-mean temperature increase of 1.5°C relative to preindustrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Annex 2.A.1.2).

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth-system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about 100 $GtCO_2$. Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below). Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 1100, 750, and 550 $GtCO_2$ (rounded to the nearest 50 $GtCO_2$) for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might bias the budget estimates. Similarly, improved understanding in Earth-system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

After TCRE uncertainty, a major additional source of uncertainty is the magnitude of non-CO_2 forcing and its contribution to the temperature change between the present day and the time of peak warming. Integrated emissions pathways can be used to ensure consistency between CO_2 and non-CO_2 emissions (Bowerman et al., 2013; Collins et al., 2013; Clarke et al., 2014; Rogelj et al., 2014b, 2015a; Tokarska et al., 2018). Friedlingstein et al. (2014a) used pathways with limited to no climate mitigation to find a variation due to non-CO_2 contributions of about ±33% for a 2°C carbon budget. Rogelj et al. (2016b) showed no particular bias in non-CO_2 radiative forcing or warming at the time of exceedance of 2°C or at peak warming between scenarios with increasing emissions and strongly mitigated scenarios (consistent with Stocker et al., 2013). However, clear differences of the non-CO_2 warming contribution at the time of deriving a 2°C-consistent carbon budget were reported for the four RCPs. Although the spread in non-CO_2 forcing across scenarios can be smaller in absolute terms at lower levels of cumulative emissions, it can be larger in relative terms compared to the remaining carbon budget (Stocker et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b). Tokarska and Gillett (2018) find no statistically significant differences in 1.5°C-consistent cumulative emissions budgets when calculated for different RCPs from consistent sets of CMIP5 simulations.

The mitigation pathways assessed in this report indicate that emissions of non-CO_2 forcers contribute an average additional warming of around 0.15°C relative to 2006–2015 at the time of net zero CO_2 emissions, reducing the remaining carbon budget by roughly 320 $GtCO_2$. This arises from a weakening of aerosol cooling and continued emissions of non-CO_2 GHGs (Sections 2.2.1, 2.3.3). This non-CO_2 contribution at the time of net zero CO_2 emissions varies by about ±0.1°C across scenarios resulting in a carbon budget uncertainty of about ±250 $GtCO_2$ and takes into account marked reductions in methane emissions (Section 2.3.3). In case these would not be achieved, remaining carbon budgets are further reduced. Uncertainties in the non-CO_2 forcing and temperature response are asymmetric and can influence the remaining carbon budget by -400 to +200 $GtCO_2$ with the uncertainty in aerosol radiative forcing being the largest contributing factor (Table 2.2). The MAGICC and FAIR models in their respective parameter setups and model versions used to assess the non-CO_2 warming contribution give noticeable different non-CO_2 effective radiative forcing and warming for the same scenarios while both being within plausible ranges of future response (Fig. 2.2 and Annex 2.A.1–2). For this assessment, it is premature to assess the accuracy of their results, so it is assumed that both are equally representative of possible futures. Their non-CO_2 warming estimates are therefore averaged for the carbon budget assessment and their differences used to guide the uncertainty assessment of the role of non-CO_2 forcers. Nevertheless, the findings are robust enough to give *high confidence* that the changing emissions non-CO_2 forcers (particularly the reduction in cooling aerosol precursors) cause additional near-term warming and reduce the remaining carbon budget compared to the CO_2 only budget.

TCRE uncertainty directly impacts carbon budget estimates (Peters, 2016; Matthews et al., 2017; Millar and Friedlingstein, 2018). Based on multiple lines of evidence, AR5 WGI assessed a *likely* range for TCRE of 0.2–0.7°C per 1000 $GtCO_2$ (Collins et al., 2013). The TCRE of the CMIP5 Earth-system models ranges from 0.23 to 0.66°C per 1000 $GtCO_2$ (Gillett et al., 2013). At the same time, studies using observational constraints find best estimates of TCRE of 0.35–0.41°C per 1000 $GtCO_2$ (Matthews et al., 2009; Gillett et al., 2013; Tachiiri et al., 2015; Millar and Friedlingstein, 2018). This assessment continues to use the assessed AR5 TCRE range under the working assumption that TCRE is normally distributed (Stocker et al., 2013). Observation-based estimates have reported log-normal distributions of TCRE (Millar and Friedlingstein, 2018). Assuming a log-normal instead of normal distribution of the assessed AR5 TCRE range would result in about a 200 $GtCO_2$ increase for the median budget estimates but only about half at the 67th percentile, while historical temperature uncertainty and uncertainty in recent emissions contribute ±150 and ±50 $GtCO_2$ to the uncertainty, respectively (Table 2.2).

Calculating carbon budgets from the TCRE requires the assumption that the instantaneous warming in response to cumulative CO_2 emissions equals the long-term warming or, equivalently, that the residual warming after CO_2 emissions cease is negligible. The magnitude of this residual warming, referred to as the zero-emission commitment, ranges from slightly negative (i.e., a slight cooling) to slightly positive for CO_2 emissions up to present-day (Section 1.2.4) (Lowe et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011; Matthews and Zickfeld, 2012). The delayed temperature change from a pulse CO_2 emission introduces uncertainties in emission budgets, which have not been quantified in the literature for budgets consistent with limiting warming to 1.5°C. As a consequence, this uncertainty does not affect our carbon budget estimates directly but it is included as an additional factor in the assessed Earth-system feedback uncertainty (as detailed below) of roughly 100 $GtCO_2$ on decadal timescales presented in Table 2.2.

Remaining carbon budgets are further influenced by Earth-system feedbacks not accounted for in CMIP5 models, such as the permafrost carbon feedback (Friedlingstein et al., 2014b; MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018), and their influence on the TCRE. Lowe and Bernie (2018) used a simple climate sensitivity scaling approach to estimate that Earth-system feedbacks (such as CO_2 released by permafrost thawing or methane released by wetlands) could reduce carbon budgets for 1.5°C and 2°C by roughly 100 $GtCO_2$ on centennial time scales. Their findings are based on older previous Earth-system feedbacks understanding (Arneth et al., 2010). This estimate is broadly supported by more recent analysis of individual feedbacks. Schädel et al. (2014) suggest an upper bound of 24.4 PgC (90 $GtCO_2$) emitted from carbon release from permafrost over the next forty years for a RCP4.5 scenario. Burke et al. (2017) use a single model to estimate permafrost emissions between 0.3 and 0.6 $GtCO_2$ y^{-1} from the point of 1.5°C stabilization, which would reduce the budget by around 20 $GtCO_2$ by 2100. Comyn-Platt et al. (2018) include methane emissions from permafrost and suggest the 1.5°C remaining carbon budget is reduced by 180 $GtCO_2$. Additionally, Mahowald et al. (2017) find there is possibility of 0.5–1.5 $GtCO_2$ y^{-1} being released from aerosol-biogeochemistry changes if aerosol emissions cease. In summary, these additional Earth system feedbacks taken together are assessed to reduce the remaining carbon budget applicable to 2100 by an order of magnitude of 100 $GtCO_2$, compared to the budgets based on the assumption of a constant TCRE presented in Table 2.2 (*limited evidence, medium agreement*), leading to overall *medium confidence* in their assessed impact.

The uncertainties presented in Table 2.2 cannot be formally combined, but current understanding of the assessed geophysical uncertainties suggests at least a ±50% possible variation for remaining carbon budgets for 1.5°C-consistent pathways. When put in the context of year-2017 CO_2 emissions (about 41 $GtCO_2$ yr^{-1}) (Le Quéré et al., 2018), a remaining carbon budget of 750 $GtCO_2$ (550 $GtCO_2$) suggests meeting net zero global CO_2 emissions in about 35 years (25 years) following a linear decline starting from 2018 (rounded to the nearest five years), with a variation of ±15–20 years due to the above mentioned geophysical uncertainties (*high confidence*).

The remaining carbon budgets assessed in this section are consistent with limiting peak warming to the indicated levels of additional warming. However, if these budgets are exceeded and the use of CDR (see Sections 2.3 and 2.4) is envisaged to return cumulative CO_2 emissions to within the carbon budget at a later point in time, additional uncertainties apply because the TCRE is different under increasing and decreasing atmospheric CO_2 concentrations due to ocean thermal and carbon-cycle inertia (Herrington and Zickfeld, 2014; Krasting et al., 2014; Zickfeld et al., 2016). This asymmetrical behaviour makes carbon budgets path-dependent in case of a budget and/or temperature overshoot (MacDougall et al., 2015). Although potentially large for scenarios with large overshoot (MacDougall et al., 2015), this path-dependence of carbon budgets has not been well quantified for 1.5°C- and 2°C-consistent scenarios and as such remains an important knowledge gap. This assessment does not explicitly account for path dependence but takes it into consideration for its overall confidence assessment.

This assessment finds a larger remaining budget from the 2006-2015 base period than the 1.5°C and 2°C remaining budgets inferred from AR5 from the start of 2011, approximately 1000 $GtCO_2$ for the 2°C (66% of model simulations) and approximately 400 $GtCO_2$ for the 1.5°C budget (66% of model simulations). In contrast, this assessment finds approximately 1600 $GtCO_2$ for the 2°C (66th TCRE percentile) and approximately 860 $GtCO_2$ for the 1.5°C budget (66th TCRE percentile) from 2011. However, these budgets are not directly equivalent as AR5 reported budgets for fractions of CMIP5 simulations and other lines of evidence, while this report uses the assessed range of TCRE and an assessment of the non-CO_2 contribution at net zero CO_2 emissions to provide remaining carbon budget estimates at various percentiles of TCRE. Furthermore, AR5 did not specify remaining budgets to carbon neutrality as we do here, but budgets until the time the temperature limit of interest was reached, assuming negligible zero emission commitment and taking into account the non-CO_2 forcing at that point in time.

In summary, although robust physical understanding underpins the carbon budget concept, relative uncertainties become larger as a specific temperature limit is approached. For the budget, applicable to the mid-century, the main uncertainties relate to the TCRE, non-CO_2 emissions, radiative forcing and response. For 2100, uncertain Earth-system feedbacks such as permafrost thawing would further reduce the available budget. The remaining budget is also conditional upon the choice of baseline, which is affected by uncertainties in both historical emissions, and in deriving the estimate of globally averaged human-induced warming. As a result, only *medium confidence* can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty.

Table 2.2: The assessed remaining carbon budget and its uncertainties. Shaded grey horizontal bands illustrate the uncertainty in historical temperature increase from the 1850-1900 base period until the 2006-2015 period, which impacts the additional warming until a specific temperature limit like 1.5°C or 2°C relative to the 1850-1900 period.

Additional warming since 2006-2015 [°C]*(1)	Approximate warming since 1850-1900 [°C]*(1)	Remaining carbon budget (excluding additional Earth-system feedbacks*(5)) [$GtCO_2$ from 1.1.2018]*(2)			Key uncertainties and variations*(4)					
		Percentiles of TCRE*(3)			Additional Earth-system feedbacks*(5)	Non-CO_2 scenario variation*(6)	Non-CO_2 forcing and response uncertainty	TCRE distribution uncertainty*(7)	Historical temperature uncertainty*(1)	Recent emissions uncertainty*(8)
		33rd	*50th*	*67th*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*
0.3		290	160	80						
0.4		530	350	230						
0.5		770	530	380	Budgets on the left are reduced by about 100 $GtCO_2$ If evaluated to 2100 and potentially more on centennial time scales					
0.6		1010	710	530						
0.63	**~1.5°C**	**1080**	**770**	**570**		+-250	-400 to +200	+100 to +200	+-250	+-20
0.7		1240	900	680						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.1		2200	1630	1280						
1.13	**~2.°C**	**2270**	**1690**	**1320**						
1.2		2440	1820	1430						

*(1) Chapter 1 has assessed historical warming between the 1850-1900 and 2006-2015 periods to be 0.87°C with a +/- 0.12°C *likely* (1-σ) range
*(2) Historical CO_2 emissions since the middle of the 1850-1900 historical base period (1 January 1876) are estimated at 1930 $GtCO_2$ (1630-2230 $GtCO_2$, 1-σ range) until end 2010. Since 1 January 2011, an additional 290 $GtCO_2$ (270-310 $GtCO_2$, 1-σ range) has been emitted until the end of 2017 (Le Quéré et al., 2018, Version 1.3 - accessed 22 May 2018).
*(3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8-2.5°C / 1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 $GtCO_2$ in the table and to the nearest 50 $GtCO_2$ in the text.
*(4) Focussing on the impact of various key uncertainties on median budgets for 0.63°C of additional warming.
*(5) Earth system feedbacks include CO_2 released by permafrost thawing or methane released by wetlands, see main text.
*(6) Variations due to different scenario assumptions related to the future evolution of non-CO_2 emissions.
*(7) The distribution of TCRE is not precisely defined. Here the influence of assuming a log-normal instead of a normal distribution shown.
*(8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

2.3 Overview of 1.5°C mitigation pathways

Limiting global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future (Zickfeld et al., 2009; Collins et al., 2013). At the same time, limiting the residual warming of short-lived non-CO_2 emissions, can be achieved by reducing their annual emissions as far as possible (Section 2.2, Cross-Chapter Box 2 in Chapter 1). This will require large-scale transformations of the global energy-agriculture-land-economy system, affecting the way in which energy is produced, agricultural systems are organised, and food, energy and materials are consumed (Clarke et al., 2014). This section assesses key properties of pathways consistent with limiting global mean temperature to 1.5°C relative to pre-industrial levels, including their underlying assumptions and variations.

Since the AR5, an extensive body of literature has appeared on integrated pathways consistent with 1.5°C (Rogelj et al., 2015b; Akimoto et al., 2017; Liu et al., 2017; Löffler et al., 2017; Marcucci et al., 2017; Su et al., 2017; Bauer et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018; Rogelj et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018) (Section 2.1). These pathways have global coverage and represent all GHG-emitting sectors and their interactions. Such integrated pathways allow the exploration of the whole-system transformation, and hence provide the context in which the detailed sectorial transformations assessed in Section 2.4 of this chapter are taking place.

The overwhelming majority of published integrated pathways have been developed by global IAMs that represent key societal systems and their interactions, like the energy system, agriculture and land use, and the economy (see Section 6.2 in Clarke et al., 2014). Very often these models also include interactions with a representation of the geophysical system, for example, by including spatially explicit land models or carbon-cycle and climate models. The complex features of these subsystems are approximated and simplified in these models. IAMs are briefly introduced in Section 2.1 and important knowledge gaps identified in Section 2.6. An overview to the use, scope and limitations of IAMs is provided in Annex 2.A.2.

The pathway literature is assessed in two ways in this section. First, various insights on specific questions reported by studies can be assessed to identify robust or divergent findings. Second, the combined body of scenarios can be assessed to identify salient features of pathways in line with a specific climate goal across a wide range of models. The latter can be achieved by assessing pathways available in the database to this assessment (Section 2.1, Annex 2.A.2–4). The ensemble of scenarios available to this assessment is an ensemble of opportunity: it is a collection of scenarios from a diverse set of studies that was not developed with a common set of questions and a statistical analysis of outcomes in mind. This means that ranges can be useful to identify robust and sensitive features across available scenarios and contributing modelling frameworks, but do not lend themselves to a statistical interpretation. To understand the reasons underlying the ranges, an assessment of the underlying scenarios and studies is required. To this end, this section highlights illustrative pathway archetypes that help to clarify the variation in assessed ranges for 1.5°C-consistent pathways.

2.3.1 Range of assumptions underlying 1.5°C pathways

Earlier assessments have highlighted that there is no single pathway to achieve a specific climate objective (e.g., Clarke et al., 2014). Pathways depend on the underlying development processes, and societal choices, which affect the drivers of projected future baseline emissions. Furthermore, societal choices also affect climate change solutions in pathways, like the technologies that are deployed, the scale at which they are deployed, or whether solutions are globally coordinated. A key finding is that 1.5°C-consistent pathways could be identified under a considerable range of assumptions in model studies despite the tightness of the 1.5°C emissions budget (Figures 2.4, 2.5) (Rogelj et al., 2018).

The AR5 provided an overview of how differences in model structure and assumptions can influence the outcome of transformation pathways (Section 6.2 in Clarke et al., 2014, as well as Table A.II.14 in Krey et al., 2014b) and this was further explored by the modelling community in recent years with regard to, e.g., socio-economic drivers (Kriegler et al., 2016; Marangoni et al., 2017; Riahi et al., 2017), technology assumptions (Bosetti et al., 2015; Creutzig et al., 2017; Pietzcker et al., 2017), and behavioural factors (van

Sluisveld et al., 2016; McCollum et al., 2017).

2.3.1.1 Socio-economic drivers and the demand for energy and land in 1.5°C-consistent pathways

There is deep uncertainty about the ways humankind will use energy and land in the 21st century. These ways are intricately linked to future population levels, secular trends in economic growth and income convergence, behavioural change and technological progress. These dimensions have been recently explored in the context of the Shared Socioeconomic Pathways (SSP) (Kriegler et al., 2012; O'Neill et al., 2014) which provide narratives (O'Neill et al., 2017) and quantifications (Crespo Cuaresma, 2017; Dellink et al., 2017; KC and Lutz, 2017; Leimbach et al., 2017; Riahi et al., 2017) of different future worlds in which scenario dimensions are varied to explore differential challenges to adaptation and mitigation (Cross-Chapter Box 1 in Chapter 1). This framework is increasingly adopted by IAMs to systematically explore the impact of socio-economic assumptions on mitigation pathways (Riahi et al., 2017), including 1.5°C-consistent pathways (Rogelj et al., 2018). The narratives describe five worlds (SSP1–5) with different socio-economic predispositions to mitigate and adapt to climate change (Table 2.3). As a result, population and economic growth projections can vary strongly across integrated scenarios, including available 1.5°C-consistent pathways (Fig. 2.4). For example, based on alternative future fertility, mortality, migration and educational assumptions, population projections vary between 8.5-10.0 billion people by 2050, and 6.9–12.6 billion people by 2100 across the SSPs. An important factor for these differences is future female educational attainment, with higher attainment leading to lower fertility rates and therewith decreased population growth up to a level of 1 billion people by 2050 (Lutz and KC, 2011; Snopkowski et al., 2016; KC and Lutz, 2017). Consistent with population development, GDP per capita also varies strongly in SSP baselines varying about 20 to more than 50 thousand USD_{2010} per capita in 2050 (in power purchasing parity values, PPP), in part driven by assumptions on human development, technological progress and development convergence between and within regions (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). Importantly, none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Hsiang et al., 2017).

Baseline projections for energy-related GHG emissions are sensitive to economic growth assumptions, while baseline projections for land-use emissions are more directly affected by population growth (assuming unchanged land productivity and per capita demand for agricultural products) (Kriegler et al., 2016). SSP-based modelling studies of mitigation pathways have identified high challenges to mitigation for worlds with a focus on domestic issues and regional security combined with high population growth (SSP3), and for worlds with rapidly growing resource and fossil-fuel intensive consumption (SSP5) (Riahi et al., 2017). No model could identify a 2°C-consistent pathway for SSP3, and high mitigation costs were found for SSP5. This picture translates to 1.5°C-consistent pathways that have to remain within even tighter emissions constraints (Rogelj et al., 2018). No model found a 1.5°C-consistent pathway for SSP3 and some models could not identify 1.5°C-consistent pathways for SSP5 (2 of 4 models, compared to 1 of 4 models for 2°C-consistent pathways). The modelling analysis also found that the effective control of land-use emissions becomes even more critical in 1.5°C-consistent pathways. Due to high inequality levels in SSP4, land use can be less well managed. This caused 2 of 3 models to no longer find an SSP4-based 1.5°C-consistent pathway even though they identified SSP4-based 2°C-consistent pathways at relatively moderate mitigation costs (Riahi et al., 2017). Rogelj et al. (2018) further reported that all six participating models identified 1.5°C-consistent pathways in a sustainability oriented world (SSP1) and four of six models found 1.5°C-consistent pathways for middle-of-the-road developments (SSP2). These results show that 1.5°C-consistent pathways can be identified under a broad range of assumptions, but that lack of global cooperation (SSP3), high inequality (SSP4) and/or high population growth (SSP3) that limit the ability to control land use emissions, and rapidly growing resource-intensive consumption (SSP5) are key impediments.

Table 2.3: Key characteristics of the five Shared Socio-economic Pathways (O'Neill et al., 2017).

Socio-economic challenges to mitigation	Socio-economic challenges to adaptation		
	Low	**Medium**	**High**
High	**SSP5: Fossil-fuelled development** • low population • very high economic growth per capita • high human development • high technological progress • ample fossil fuel resources • resource intensive lifestyles • high energy and food demand per capita • convergence and global cooperation		**SSP3: Regional rivalry** • high population • low economic growth per capita • low human development • low technological progress • resource intensive lifestyles • resource constrained energy and food demand per capita • focus on regional food and energy security • regionalization and lack of global cooperation
Medium		**SSP2: Middle of the road** • medium population • medium and uneven economic growth • medium and uneven human development • medium and uneven technological progress • resource intensive lifestyles • medium and uneven energy and food demand per capita • limited global cooperation and convergence	
Low	**SSP1: Sustainable development** • low population • high economic growth per capita • high human development • high technological progress • environmentally oriented technological and behavioural change • resource efficient lifestyles • low energy and food demand per capita • convergence and global cooperation		**SSP4: Inequality** • Medium to high population • Unequal low to medium economic growth per capita • Unequal low to medium human development • unequal technological progress: high in globalized high tech sectors, slow in domestic sectors • unequal lifestyles and energy / food consumption: resource intensity depending on income • Globally connected elite, disconnected domestic work forces

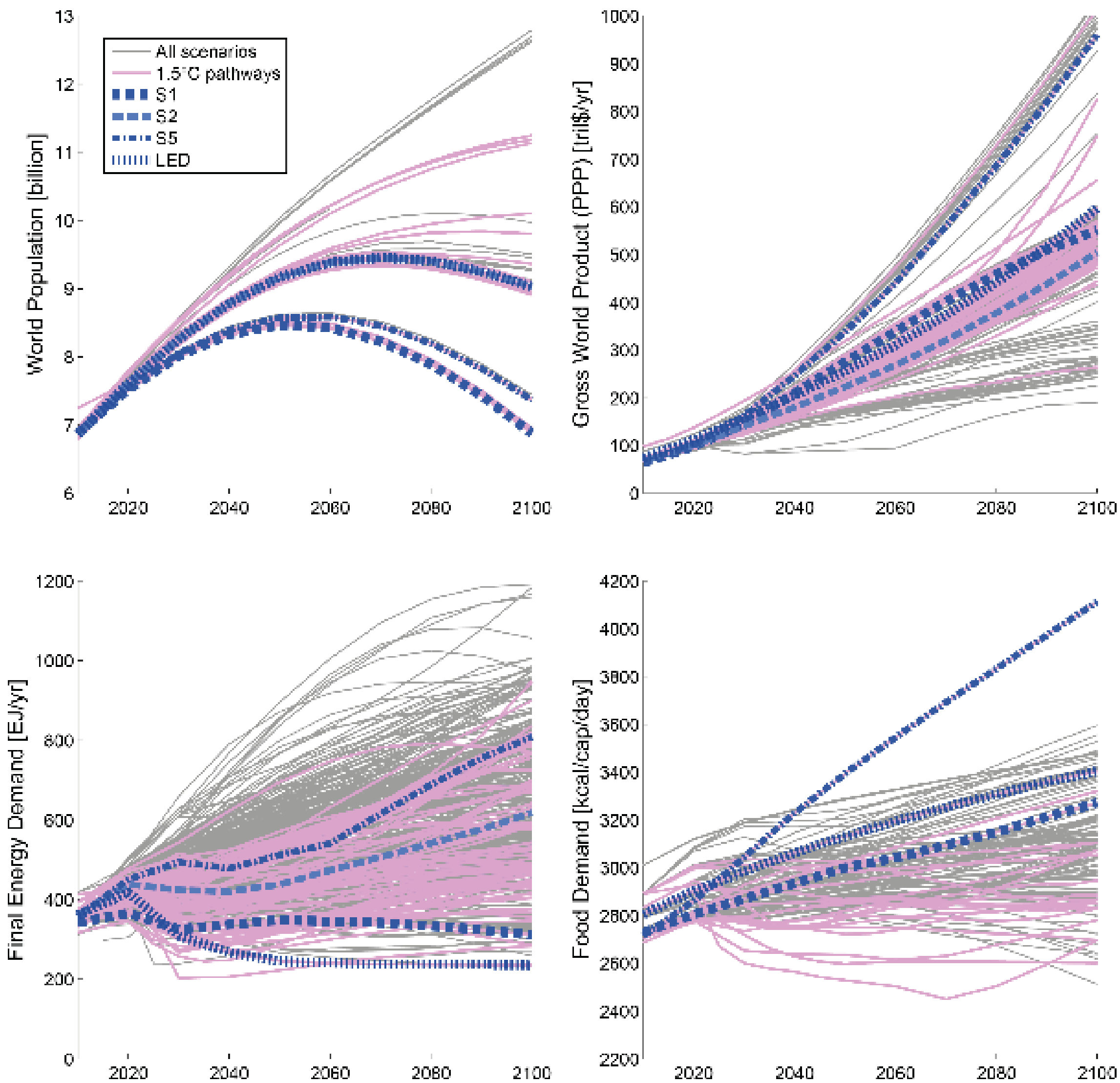

Figure 2.4: Range of assumptions about socio-economic drivers and projections for energy and food demand in the pathways available to this assessment. 1.5°C-consistent pathways are pink, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (*S1*, *S2*, *S3*, *LED*) are highlighted. Population assumptions in *S2* and *LED* are identical.

Figure 2.4 compares the range of underlying socio-economic developments as well as energy and food demand in available 1.5°C-consistent pathways with the full set of published scenarios that were submitted to this assessment. While 1.5°C-consistent pathways broadly cover the full range of population and economic growth developments (except of the high population development in SSP3-based scenarios), they tend to cluster on the lower end for energy and food demand. They still encompass, however, a wide range of developments from decreasing to increasing demand levels relative to today. For the purpose of this assessment, a set of four illustrative 1.5°C-consistent pathway archetypes were selected to show the variety of underlying assumptions and characteristics (Fig. 2.4). They comprise three 1.5°C-consistent pathways based on the SSPs (Rogelj et al., 2018): a sustainability oriented scenario (*S1* based on SSP1) developed with the AIM model (Fujimori, 2017), a fossil-fuel intensive and high energy demand scenario (*S5*, based on SSP5) developed with the REMIND-MAgPIE model (Kriegler et al., 2017), and a middle-of-the-road scenario (*S2*, based on SSP2) developed with the MESSAGE-GLOBIOM model (Fricko et al., 2017). In addition, we include a scenario with low energy demand (*LED*) (Grubler et al., 2018), which reflects recent literature with a stronger focus on demand-side measures (Liu et al., 2017; Bertram et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018).

2.3.1.2 *Mitigation options in 1.5°C-consistent pathways*

In the context of 1.5°C-consistent pathways, the portfolio of mitigation options available to the model becomes an increasingly important factor. IAMs include a wide variety of mitigation options, as well as measures that achieve CDR from the atmosphere (Krey et al., 2014a, 2014b) (see Section 4.3 for a broad assessment of available mitigation measures). For the purpose of this assessment, we elicited technology availability in models that submitted scenarios to the database as summarized in Annex 2.A.2, where a detailed picture of the technology variety underlying available 1.5°C-consistent pathways is provided. Modelling choices on whether a particular mitigation measure is included are influenced by an assessment of its global mitigation potential, the availability of data and literature describing its techno-economic characteristics and future prospects, and computational challenge to represent the measure, e.g., in terms of required spatio-temporal and process detail.

This elicitation (Annex 2.A.2) confirms that IAMs cover most supply-side mitigation options on the process level, while many demand-side options are treated as part of underlying assumptions, which can be varied (Clarke et al., 2014). In recent years, there has been increasing attention on improving the modelling of integrating variable renewable energy into the power system (Creutzig et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017) and of behavioural change and other factors influencing future demand for energy and food (van Sluisveld et al., 2016; McCollum et al., 2017; Weindl et al., 2017), including in the context of 1.5°C-consistent pathways (Grubler et al., 2018; van Vuuren et al., 2018). The literature on the many diverse CDR options only recently started to develop strongly (Minx et al., 2017) (see Section 4.3.7 for a detailed assessment), and hence these options are only partially included in IAM analyses. IAMs mostly incorporate afforestation and bioenergy with carbon capture and storage (BECCS) and only in few cases also include direct air capture with CCS (DACCS) (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b).

Several studies have either directly or indirectly explored the dependence of 1.5°C-consistent pathways on specific (sets of) mitigation and CDR technologies (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Rogelj et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). However, there are a few potentially disruptive technologies that are typically not yet well covered in IAMs and that have the potential to alter the shape of mitigation pathways beyond the ranges in the IAM-based literature. Those are also included in Annex 2.A.2. The configuration of carbon-neutral energy systems projected in mitigation pathways can vary widely, but they all share a substantial reliance on bioenergy under the assumption of effective land-use emissions control. There are other configurations with less reliance on bioenergy that are not yet comprehensively covered by global mitigation pathway modelling. One approach is to dramatically reduce and electrify energy demand for transportation and manufacturing to levels that make residual non-electric fuel use negligible or replaceable by limited amounts of electrolytic hydrogen. Such an approach is presented in a first-of-its kind low energy demand scenario (Grubler et al., 2018) which is part of this assessment. Other approaches rely less on energy demand reductions, but employ cheap renewable electricity to push the boundaries of electrification in the industry and transport sectors (Breyer et al., 2017; Jacobson, 2017). In addition, these approaches deploy renewable-based Power-2-X (read: Power to "x") technologies to substitute residual fossil-fuel use (Brynolf et al., 2018). An important element of carbon-neutral Power-2-X applications is the combination of hydrogen generated from renewable electricity and CO_2 captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with more limited implications for land use and agricultural systems than energy crops (Williams and Laurens, 2010; Walsh et al., 2016; Greene et al., 2017).

Furthermore, a range of measures could radically reduce agricultural and land-use emissions and are not yet well-covered in IAM modelling. This includes plant-based proteins (Joshi and Kumar, 2015) and cultured meat (Post, 2012) with the potential to substitute for livestock products at much lower GHG footprints (Tuomisto and Teixeira de Mattos, 2011). Large-scale use of synthetic or algae-based proteins for animal feed could free pasture land for other uses (Madeira et al., 2017; Pikaar et al., 2018). Novel technologies such as methanogen inhibitors and vaccines (Wedlock et al., 2013; Hristov et al., 2015; Herrero et al., 2016; Subharat et al., 2016) as well as synthetic and biological nitrification inhibitors (Subbarao et al., 2013; Jie Di and Cameron, 2016) could substantially reduce future non-CO_2 emissions from agriculture if commercialised successfully. Enhancing carbon sequestration in soils (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017) can provide the dual benefit of CDR and improved soil quality. A range of conservation, restoration and land management options can also increase terrestrial carbon uptake (Griscom et al., 2017). In addition, the literature discusses CDR measures to permanently sequester atmospheric carbon in rocks (mineralisation and enhanced weathering, see Section 4.3.7) as well as carbon capture and usage in long-lived products like plastics and carbon fibres (Mazzotti et al., 2005; Hartmann et al., 2013). Progress in the understanding of the technical viability, economics, and sustainability of these ways to achieve and maintain carbon neutral energy and land use can affect the characteristics, costs and feasibility of 1.5°C-consistent pathways significantly.

2.3.1.3 *Policy assumptions in 1.5°C-consistent pathways*

Besides assumptions related to socio-economic drivers and mitigation technology, scenarios are also subject to assumptions about the mitigation policies that can be put in place. Mitigation policies can either be applied immediately in scenarios or follow staged or delayed approaches. Policies can span many sectors (e.g., economy-wide carbon pricing), or policies can be applicable to specific sectors only (like the energy sector) with other sectors (e.g., the agricultural or the land-use sector) treated differently. These variations can have an important impact on the ability of models to generate scenarios compatible with stringent climate targets like 1.5°C (Luderer et al., 2013; Rogelj et al., 2013; Bertram et al., 2015b; Kriegler et al., 2018b; Michaelowa et al., 2018). In the scenario ensemble available to this assessment, several variations of near-term mitigation policy implementation can be found: immediate and cross-sectorial global cooperation from 2020 onward towards a global climate objective, a phase-in of globally coordinated mitigation policy from 2020 to 2040, and a more short-term oriented and regionally diverse global mitigation policy, following NDCs until 2030 (Kriegler et al., 2018b; Luderer et al., 2018; McCollum et al., 2018; Rogelj et al., 2018; Strefler et al., 2018b). For example, above-mentioned SSP quantifications assume regionally scattered mitigation policies until 2020, and vary in global convergence thereafter (Kriegler et al., 2014a; Riahi et al., 2017). The impact of near-term policy choices on 1.5°C-consistent pathways is discussed in Section 2.3.5. The literature has also explored 1.5°C-consistent pathways building on a portfolio of policy approaches until 2030, including the combination of regulatory policies and carbon pricing (Kriegler et al., 2018b) and a variety of ancillary policies to safeguard other sustainable development goals (Bertram et al., 2018; van Vuuren et al., 2018). A further discussion of policy implications of 1.5°C-consistent pathways is provided in Section 2.5.1, while a general discussion of policies and options to strengthen action are subject of Section 4.4.

2.3.2 Key characteristics of 1.5°C-consistent pathways

1.5°C-consistent pathways are characterised by a rapid phase out of CO_2 emissions and deep emissions reductions in other GHGs and climate forcers (Section 2.2.2 and 2.3.3). This is achieved by broad transformations in the energy, industry, transport, buildings, Agriculture, Forestry and Other Land-Use (AFOLU) sectors (Section 2.4) (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Luderer et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018; Zhang et al., 2018). Here we assess 1.5°C-consistent pathways with and without overshoot during the 21st century. One study also explores pathways overshooting 1.5°C for longer than the 21st century (Akimoto et al., 2017), but these are not considered 1.5°C-consistent pathways in this report (Section 1.1.3). This subsection summarizes robust and varying properties of 1.5°C-consistent pathways regarding system transformations, emission reductions and overshoot. It aims to provide an introduction to the detailed assessment of the emissions evolution (Section 2.3.3), CDR deployment (Section 2.3.4), energy (Section 2.4.1, 2.4.2), industry (2.4.3.1), buildings (2.4.3.2), transport (2.4.3.3) and land-use transformations (Section 2.4.4) in 1.5°C-consistent pathways. Throughout Sections 2.3 and 2.4, pathway properties are highlighted with four 1.5°C-consistent pathway archetypes (*S1*, *S2*, *S5*, *LED*) covering a wide range of different socio-economic and technology assumptions (Fig. 2.5, Section 2.3.1).

2.3.2.1 *Variation in system transformations underlying 1.5°C-consistent pathways*

Be it for the energy, transport, buildings, industry, or AFOLU sector, the literature shows that multiple options and choices are available in each of these sectors to pursue stringent emissions reductions (Section

2.3.1.2, Annex 2.A.2, Section 4.3). Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). A robust feature of 1.5°C-consistent pathways, as highlighted by the set of pathway archetypes in Figure 2.5, is a virtually full decarbonisation of the power sector around mid-century, a feature shared with 2°C-consistent pathways. The additional emissions reductions in 1.5°C-consistent compared to 2°C-consistent pathways come predominantly from the transport and industry sectors (Luderer et al., 2018). Emissions can be apportioned differently across sectors, for example, by focussing on reducing the overall amount of CO_2 produced in the energy end use sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, *S1* and *LED* pathways in Figure 2.5) (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018), or by being more lenient about the amount of CO_2 that continues to be produced in the above-mentioned end-use sectors (both by 2030 and mid-century) and strongly relying on technological CDR options like BECCS (*S2* and *S5* pathways in Figure 2.5) (Luderer et al., 2018; Rogelj et al., 2018). Major drivers of these differences are assumptions about energy and food demand and the stringency of near term climate policy (see the difference between early action in the scenarios *S1*, *LED* and more moderate action until 2030 in the scenarios *S2*, *S5*). Furthermore, the carbon budget in each of these pathways depends also on the non-CO_2 mitigation measures implemented in each of them, particularly for agricultural emissions (Sections 2.2.2, 2.3.3) (Gernaat et al., 2015). Those pathways differ not only in terms of their deployment of mitigation and CDR measures (Sections 2.3.4 and 2.4), but also in terms of the temperature overshoot they imply (Figure 2.1). Furthermore, they have very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

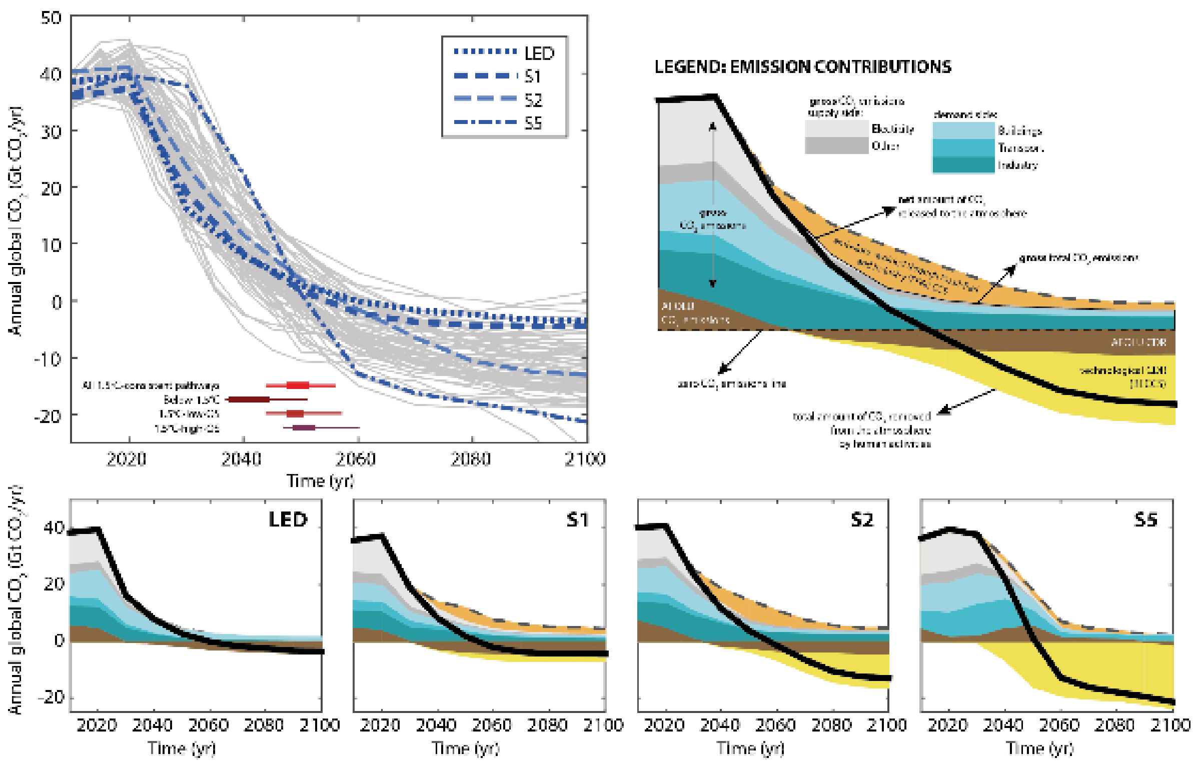

Figure 2.5: Evolution and break down of global anthropogenic CO_2 emissions until 2100. The top-left panel shows global net CO_2 emissions in Below-1.5°C, 1.5°C-low-OS, and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at the bottom of the top-left panel show the 10^{th}–90^{th} percentile range (thin line) and interquartile range (thick line) of the time that global CO_2 emissions reach net zero per pathway class, and for all pathways classes combined. The top-right panel provides a schematic legend explaining all CO_2 emissions contributions to global CO_2 emissions. The bottom row shows how various CO_2 contributions are deployed and used in the four illustrative pathway archetypes (*S1*, *S2*, *S5*, and *LED*) used in this chapter. Note that the S5 scenario reports the building and industry sector emissions jointly. Green-blue areas hence show emissions from the transport, and building & industry demand sectors, respectively.

2.3.2.2 *Pathways keeping warming below 1.5°C or temporarily overshooting it*

This subsection explores the conditions that would need to be fulfilled to stay below 1.5°C warming without overshoot. As discussed in Section 2.2.2, to keep warming below 1.5°C with a two-in-three (one-in-two) chance, the cumulative amount of CO_2 emissions from 2018 onwards need to remain below a carbon budget of 550 (750) $GtCO_2$, further reduced by 100 $GtCO_2$ when accounting for additional Earth-system feedbacks until 2100. Based on the current state of knowledge, exceeding this remaining carbon budget at some point in time would give a one-in-three (one-in-two) chance that the 1.5°C limit is overshot (Table 2.2). For comparison, around 290 ±20 (1-sigma range) $GtCO_2$ have been emitted in the years 2011-2017 with annual CO_2 emissions in 2017 slightly above 40 $GtCO_2\ yr^{-1}$ (Jackson et al., 2017; Le Quéré et al., 2018). Committed fossil-fuel emissions from existing fossil-fuel infrastructure as of 2010 have been estimated at around 500 ±200 $GtCO_2$ (with ca. 200 $GtCO_2$ already emitted until 2017) (Davis and Caldeira, 2010). Coal-fired power plants contribute the largest part. Committed emissions from existing coal-fired power plants built until the end of 2016 are estimated to add up to roughly 200 $GtCO_2$ and a further 100–150 $GtCO_2$ from coal-fired power plants are under construction or planned (González-Eguino et al., 2017; Edenhofer et al., 2018). However, there has been a marked slowdown of planned coal-power projects in recent years, and some estimates indicate that the committed emissions from coal plants that are under construction or planned have halved since 2015 (Shearer et al., 2018). Despite these uncertainties, the committed fossil-fuel emissions are assessed to already amount to more than half (a third) of the remaining carbon budget.

An important question is to what extent the nationally determined contributions (NDCs) under the Paris Agreement are aligned with the remaining carbon budget. It was estimated that the NDCs, if successfully implemented, imply a total of 400–560 $GtCO_2$ emissions over the 2018–2030 period (considering both conditional and unconditional NDCs) (Rogelj et al., 2016a). Thus, following an NDC trajectory would exhaust already 70–100% (50–75%) of the remaining two-in-three (one-in-two) 1.5°C carbon budget (unadjusted for additional Earth-system feedbacks) by 2030. This would leave only about 0–8 (9–18) years to bring down global emissions from NDC levels of around 40 $GtCO_2\ yr^{-1}$ in 2030 (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero (further discussion in Section 2.3.5).

Most 1.5°C-consistent pathways show more stringent emissions reductions by 2030 than implied by the NDCs (Section 2.3.5) The lower end of those pathways reach down to below 20 $GtCO_2\ yr^{-1}$ in 2030 (Section 2.3.3, Table 2.4), less than half of what is implied by the NDCs. Whether such pathway will be able to limit warming to 1.5°C without overshoot will depend on whether cumulative net CO_2 emissions over the 21st century can be kept below the remaining carbon budget at any time. Net global CO_2 emissions are derived from the gross amount of CO_2 that humans annually emit into the atmosphere reduced by the amount of anthropogenic CDR in each year. New research has looked more closely at the amount and the drivers of gross CO_2 emissions from fossil-fuel combustion and industrial processes (FFI) in deep mitigation pathways (Luderer et al., 2018), and found that the larger part of remaining CO_2 emissions come from direct fossil-fuel use in the transport and industry sectors, while residual energy supply sector emissions (mostly from the power sector) are limited by a rapid approach to net zero CO_2 emissions until mid-century. The 1.5°C-consistent pathways from the literature that were reported in the scenario database project remaining FFI CO_2 emissions of 620–1410 $GtCO_2$ over the period 2018–2100 (5th–95th percentile range; median: 970 $GtCO_2$). Kriegler et al. (2018a) conducted a sensitivity analysis that explores the four central options for reducing fossil-fuel emissions: lowering energy demand, electrifying energy services, decarbonizing the power sector and decarbonizing non-electric fuel use in energy end-use sectors. By exploring these options to their extremes, they found a lowest value of 500 $GtCO_2$ (2018–2100) gross fossil-fuel CO_2 emissions for the hypothetical case of aligning the strongest assumptions for all four mitigation options. The two lines of evidence and the fact that available 1.5°C pathways cover a wide range of assumptions (Section 2.3.1) give a robust indication of a lower limit of ca. 500 $GtCO_2$ remaining fossil-fuel and industry CO_2 emissions in the 21st century.

To compare these numbers with the remaining carbon budget, Land-Use Change (LUC) CO_2 emissions need to be taken into account. In many of the 1.5°C-consistent pathways LUC CO_2 emissions reach zero at or before mid-century and then turn to negative values (Table 2.4). This means human changes to the land lead to atmospheric carbon being stored in plants and soils. This needs to be distinguished from the natural CO_2

uptake by land which is not accounted for in the anthropogenic LUC CO_2 emissions reported in the pathways. Given the difference in estimating the 'anthropogenic' sink between countries and the global integrated assessment and carbon modelling community (Grassi et al., 2017), the LUC CO_2 estimates included here are not necessarily directly comparable with countries' estimates at global level. The cumulated amount of LUC CO_2 emissions until the time they reach zero combine with the fossil-fuel and industry CO_2 emissions to a total amount of gross emissions of 670–1430 $GtCO_2$ for the period 2018–2100 (5th–95th percentile; median 1040 $GtCO_2$). The lower end of the range is similar to what emerges from a scenario of transformative change that halves CO_2 emissions every decade from 2020 to 2050 (Rockström et al., 2017). All these estimates are above the remaining carbon budget for a two-in-three chance of limiting warming below 1.5°C without overshoot, including the low end of the hypothetical sensitivity analysis of Kriegler et al. (2018a), who assumes 75 $GtCO_2$ LUC emissions adding to a total of 575 $GtCO_2$ gross CO_2 emissions. As only limited, highly idealized cases have been identified that keep gross CO_2 emissions within the 1.5°C carbon budget and based on current understanding of the geophysical response and its uncertainties, the available evidence indicates that avoiding overshoot will require some type of CDR in a broad sense, e.g., via negative LUC CO_2 emissions. (*medium confidence*) (Table 2.2).

Net CO_2 emissions can fall below gross CO_2 emissions, if CDR is brought into the mix. Studies have looked at mitigation and CDR in combination to identify strategies for limiting warming to 1.5°C (Sanderson et al., 2016; Ricke et al., 2017). CDR and/or negative LUC CO_2 emissions are deployed by all 1.5°C-consistent pathways available to this assessment, but the scale of deployment and choice of CDR measure varies widely (Section 2.3.4). Furthermore, no CDR technology has been deployed at scale yet, and all come with concerns about their potential (Fuss et al., 2018), feasibility (Nemet et al., 2018) and/or sustainability (Smith et al., 2015; Fuss et al., 2018) (see Sections 2.3.4, 4.3.2 and 4.3.7 and Cross-Chapter Box 7 in Chapter3 for further discussion). CDR can have two very different functions in 1.5°C-consistent pathways. If deployed in the first half of the century, before net zero CO_2 emissions are reached, it neutralizes some of the remaining CO_2 emissions year by year and thus slows the accumulation of CO_2 in the atmosphere. In this first function it can be used to remain within the carbon budget and avoid overshoot. If CDR is deployed in the second half of the century after carbon neutrality has been established, it can still be used to neutralize some residual emissions from other sectors, but also to create net negative emissions that actively draw down the cumulative amount of CO_2 emissions to return below a 1.5°C warming level. In the second function, CDR enables temporary overshoot. The literature points to strong limitations to upscaling CDR (limiting its first abovementioned function) and to sustainability constraints (limiting both abovementioned functions) (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018). Large uncertainty hence exists about what amount of CDR could actually be available before mid-century. Kriegler et al. (2018a) explore a case limiting CDR to 100 $GtCO_2$ until 2050, and the 1.5°C-consistent pathways available in the report's database project 40–260 $GtCO_2$ CDR until the point of carbon neutrality (5^{th} to 95^{th} percentile; median 120 $GtCO_2$). Because gross CO_2 emissions in most cases exceed the remaining carbon budget by several hundred $GtCO_2$ and given the limits to CDR deployment until 2050, most of the 1.5°C-consistent pathways available to this assessment are overshoot pathways. However, the scenario database also contains nine non-overshoot pathways that remain below 1.5°C throughout the 21st century and that are assessed in the chapter.

2.3.3 Emissions evolution in 1.5°C pathways

This section assesses the salient temporal evolutions of climate forcers over the 21st century. It uses the classification of 1.5°C-consisten pathways presented in Section 2.1, which includes a Below-1.5°C class, as well as other classes with varying levels of projected overshoot (1.5°C-low-OS and 1.5°C-high-OS). First, aggregate-GHG benchmarks for 2030 are assessed. Subsequent sections assess long-lived climate forcers (LLCF) and short-lived climate forcers (SLCF) separately because they contribute in different ways to near-term, peak and long-term warming (Section 2.2, Cross-Chapter Box 2 in Chapter 1).

Estimates of aggregated GHG emissions in line with specific policy choices are often compared to near-term benchmark values from mitigation pathways to explore their consistency with long-term climate goals (Clarke et al., 2014; UNEP, 2016, 2017; UNFCCC, 2016). Benchmark emissions or estimates of peak years derived from IAMs provide guidelines or milestones that are consistent with achieving a given temperature level. While they do not set mitigation requirements in a strict sense, exceeding these levels in a given year almost invariably increases the mitigation challenges afterwards by increasing the rates of change and increasing the reliance on speculative technologies, including the possibility that its implementation becomes unachievable (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014; Fawcett et al., 2015; Riahi et al., 2015; Kriegler et al., 2018b) (see Cross-Chapter Box 3 in Chapter 1 for a discussion of feasibility concepts). These trade-offs are particularly pronounced in 1.5°C-consistent pathways and are discussed in Section 2.3.5. This section assesses Kyoto-GHG emissions in 2030 expressed in CO_2 equivalent (CO_2e) emissions using 100-year global warming potentials[3].

Appropriate benchmark values of aggregated GHG emissions depend on a variety of factors. First and foremost, they are determined by the desired likelihood to keep warming below 1.5°C and the extent to which projected temporary overshoot is to be avoided (Sections 2.2, 2.3.2, and 2.3.5). For instance, median aggregated 2030 GHG emissions are about 10 $GtCO_2e$ yr^{-1} lower in 1.5°C-low-OS compared to 1.5°C-high-OS pathways, with respective interquartile ranges of 26–31 and 36–49 $GtCO_2e$ yr^{-1} (Table 2.4). These ranges correspond to 25–30 and 35–48 $GtCO_2e$ yr^{-1} in 2030, respectively, when aggregated with 100-year Global Warming Potentials from the IPCC Second Assessment Report. The limited evidence available for pathways aiming to limit warming below 1.5°C without overshoot or with limited amounts of CDR (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018) indicates that under these conditions consistent emissions in 2030 would fall at the lower end and below the abovementioned ranges. Ranges for the 1.5°C-low-OS and Lower-2°C classes only overlap outside their interquartile ranges highlighting the more accelerated reductions in 1.5°C-consistent compared to 2°C-consistent pathways.

Appropriate benchmark values also depend on the acceptable or desired portfolio of mitigation measures, representing clearly identified trade-offs and choices (Sections 2.3.4, 2.4, and 2.5.3) (Luderer et al., 2013; Rogelj et al., 2013a; Clarke et al., 2014; Krey et al., 2014a; Strefler et al., 2018b). For example, lower 2030 GHG emissions correlate with a lower dependence on the future availability and desirability of CDR (Strefler et al., 2018b). Explicit choices or anticipation that CDR options are only deployed to a limited degree during the 21st century imply lower benchmarks over the coming decades that are achieved through lower CO_2 emissions. The pathway archetypes used in the chapter illustrate this further (Figure 2.6). Under middle-of-the-road assumptions of technological and socioeconomic development, pathway *S2* suggests emission benchmarks of 34, 12 and -8 $GtCO_2e$ yr^{-1} in the years 2030, 2050, and 2100, respectively. In contrast, a pathway that further limits overshoot and aims at eliminating the reliance on negative emissions technologies like BECCS as well as CCS (here labelled as the *LED* pathway) shows deeper emissions reductions in 2030 to limit the cumulative amount of CO_2 until net zero global CO_2 emissions (carbon neutrality). The *LED* pathway here suggest emission benchmarks of 25, 9 and 2 $GtCO_2e$ yr^{-1} in the years 2030, 2050, and 2100, respectively. However, a pathway that allows and plans for the successful large-scale deployment of BECCS by and beyond 2050 (*S5*) shows a shift in the opposite direction. The variation within and between the abovementioned ranges of 2030 GHG benchmarks hence depends strongly on societal choices and preferences related to the acceptability and availability of certain technologies.

Overall these variations do not strongly affect estimates of the 1.5°C-consistent timing of global peaking of GHG emissions. Both Below-1.5°C and 1.5°C-low-OS pathways show minimum-maximum ranges in 2030 that do not overlap with 2020 ranges, indicating the global GHG emissions peaked before 2030 in these pathways. Also 2020 and 2030 GHG emissions in 1.5°C-high-OS pathways only overlap outside their interquartile ranges.

Kyoto-GHG emission reductions are achieved by reductions in CO_2 and non-CO_2 GHGs. The AR5 identified two primary factors that influence the depth and timing of reductions in non-CO_2 Kyoto-GHG emissions: (1) the abatement potential and costs of reducing the emissions of these gases and (2) the strategies that allow making trade-offs between them (Clarke et al., 2014). Many studies indicate low-cost near-term mitigation options in some sectors for non-CO_2 gases compared to supply-side measures for CO_2 mitigation (Clarke et al., 2014). A large share of this potential is hence already exploited in mitigation pathways in line with 2°C. At the same time, by mid-century and beyond, estimates of further reductions of non-CO_2 Kyoto-GHGs, in

[3] FOOTNOTE: In this chapter GWP-100 values from the IPCC Fourth Assessement Report are used because emissions of fluorinated gases in the integrated pathways have been reported in this metric to the database. At a global scale, switching between GWP-100 values of the Second, Fourth or Fifth IPCC Assessment Reports could result in variations in aggregated Kyoto-GHG emissions of about ±5% in 2030 (UNFCCC, 2016).

particular CH_4 and N_2O, are hampered by the absence of mitigation options in the current generation of IAMs which are hence not able to reduce residual emissions of sources linked to livestock production and fertilizer use (Clarke et al., 2014; Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Annex 2.A.2). Therefore, while net CO_2 emissions are projected to be markedly lower in 1.5°C-consistent compared to 2°C-consistent pathways, this is much less the case for methane (CH_4) and nitrous-oxide (N_2O) (Figures 2.6–2.7). This results in reductions of CO_2 being projected to take up the largest share of emissions reductions when moving between 1.5°C-consistent and 2°C-consistent pathways (Rogelj et al., 2015b, 2018; Luderer et al., 2018). If additional non-CO_2 mitigation measures are identified and adequately included in IAMs, they are expected to further contribute to mitigation efforts by lowering the floor of residual non-CO_2 emissions. However, the magnitude of these potential contributions has not been assessed as part of this report.

The interplay between residual CO_2 and non-CO_2 emissions, as well as CDR results in different times at which global GHG emissions reach net zero levels in 1.5°C-consistent pathways. Interquartile ranges of the years in which 1.5°C-low-OS and 1.5°C-high-OS reach net zero GHG emissions range from 2060 to 2080 (Table 2.4). A seesaw characteristic can be found between near-term emissions reductions and the timing of net zero GHG emissions as a result of the reliance on net negative emissions of pathways with limited emissions reductions in the next one to two decades (see earlier). Most 1.5°C-high-OS pathways lead to net zero GHG emissions in approximately the third quarter of this century, because all of them rely on significant amounts of annual net negative emissions in the second half of the century to decline temperatures after overshoot (Table 2.4). However, emissions in pathways that aim at limiting overshoot as much as possible or more slowly decline temperatures after their peak reach this point slightly later or at times never. Early emissions reductions in this case result in a lower requirement for net negative emissions. Estimates of 2030 GHG emissions in line with the current NDCs overlap with the highest quartile of 1.5°C-high-OS pathways (Cross-Chapter Box 9 in Chapter 4).

2.3.3.1 *Emissions of long-lived climate forcers*

Climate effects of long-lived climate forcers (LLCFs) are dominated by CO_2, with smaller contributions of N_2O and some fluorinated gases (Myhre et al., 2013; Blanco et al., 2014). Overall net CO_2 emissions in pathways are the result of a combination of various anthropogenic contributions (Figure 2.5) (Clarke et al., 2014): (a) CO_2 produced by fossil-fuel combustion and industrial processes, (b) CO_2 emissions or removals from the Agriculture, Forestry and Other Land Use (AFOLU) sector, (c) CO_2 capture and sequestration (CCS) from fossil fuels or industrial activities before it is released to the atmosphere, (d) CO_2 removal by technological means, which in current pathways is mainly achieved by BECCS although other options could be conceivable (see Section 4.3.7). Pathways apply these four contributions in different configurations (Figure 2.5) depending on societal choices and preferences related to the acceptability and availability of certain technologies, the timing and stringency of near-term climate policy, and the ability to limit the demand that drives baseline emissions (Marangoni et al., 2017; Riahi et al., 2017; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018), and come with very different implication for sustainable development (Section 2.5.3).

All 1.5°C-consistent pathways see global CO_2 emissions embark on a steady decline to reach (near) net zero levels around 2050, with 1.5°C-low-OS pathways reaching net zero CO_2 emissions around 2045–2055 (Table 2.4; Figure 2.5). Near-term differences between the various pathway classes are apparent, however. For instance, Below-1.5°C and 1.5°C-low-OS pathways show a clear shift towards lower CO_2 emissions in 2030 relative to other 1.5°C and 2°C pathway classes, although in all 1.5°C-consistent classes reductions are clear (Figure 2.6). These lower near-term emissions levels are a direct consequence of the former two pathway classes limiting cumulative CO_2 emissions until carbon neutrality to aim for a higher probability that peak warming is limited to 1.5°C (Section 2.2.2 and 2.3.2.2). In some cases, 1.5°C-low-OS pathways achieve net zero CO_2 emissions one or two decades later, contingent on 2030 CO_2 emissions in the lower quartile of the literature range, i.e. below about 18 $GtCO_2$ yr^{-1}. Median year-2030 global CO_2 emissions are of the order of 5–10 $GtCO_2$ yr^{-1} lower in Below-1.5°C compared to 1.5°C-low-OS pathways, which are in turn lower than 1.5°C-high-OS pathways (Table 2.4). 1.5°C-high-OS pathways show broadly similar emissions levels than the 2°C-consistent pathways in 2030.

The development of CO_2 emissions in the second half of the century in 1.5°C pathways is characterised by the need to stay or return within a carbon budget. Figure 2.6 shows net CO_2 and N_2O emissions from various sources in 2050 and 2100 in 1.5°C-consistent pathways in the literature. Virtually all 1.5°C pathways obtain net negative CO_2 emissions at some point during the 21st century but the extent to which net negative emissions are relied upon varies substantially (Figure 2.6, Table 2.4). This net withdrawal of CO_2 from the atmosphere compensates for residual long-lived non-CO_2 GHG emissions that also accumulate in the atmosphere (like N_2O) or to cancel some of the build-up of CO_2 due to earlier emissions to achieve increasingly higher likelihoods that warming stays or returns below 1.5°C (see Section 2.3.4 for a discussion of various uses of CDR). Even non-overshoot pathways that aim at achieving temperature stabilisation would hence deploy a certain amount of net negative emissions to offset any accumulating long-lived non-CO_2 GHGs. 1.5°C overshoot pathways display significantly larger amounts of annual net negative emissions in the second half of the century. The larger the overshoot the more net negative emissions are required to return temperatures to 1.5°C by the end of the century (Table 2.4, Figure 2.1).

N_2O emissions decline to a much lesser extent than CO_2 in currently available 1.5°C-consistent pathways (Figure 2.6). Current IAMs have limited emissions reduction potentials (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Annex 2.A.2), reflecting the difficulty of eliminating N_2O emission from agriculture (Bodirsky et al., 2014). Moreover, the reliance of some pathways on significant amounts of bioenergy after mid-century (Section 2.4.2) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017) also makes reducing N_2O emissions harder (for example, see pathway *S5* in Figure 2.6). As a result, sizeable residual N_2O emissions are currently projected to continue throughout the century, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies. Finally, the reduction of nitrogen use and N_2O emissions from agriculture is already a present-day concern due to unsustainable levels of nitrogen pollution (Bodirsky et al., 2012). Section 2.4.4 provides a further assessment of the agricultural non-CO_2 emissions reduction potential.

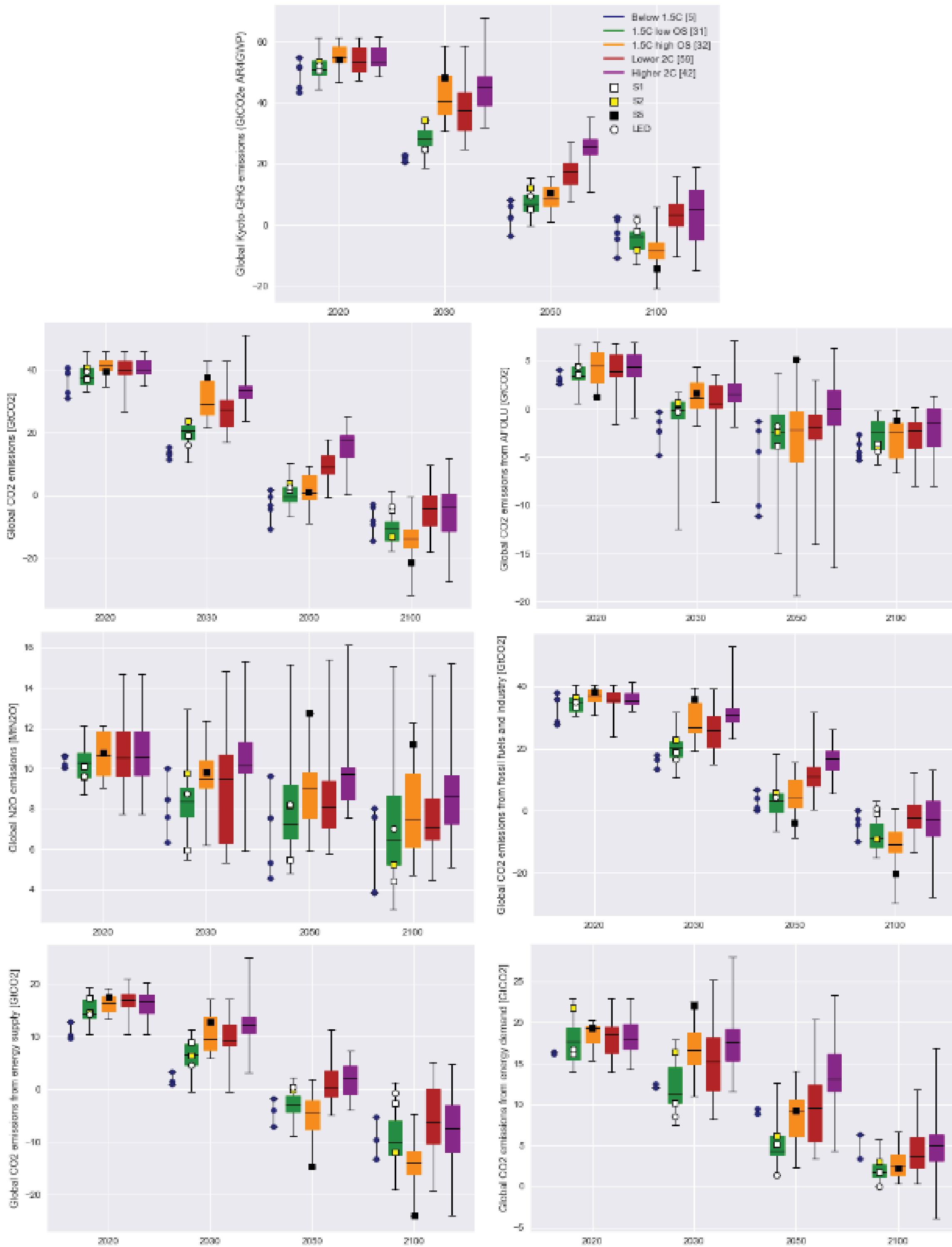

Figure 2.6: **Annual global emissions characteristics for 2020, 2030, 2050, 2100.** Data are shown for Kyoto-GHG emissions (top panel), and total CO_2 emissions, CO_2 emissions from the AFOLU sector, global N_2O emissions, and CO_2 emissions from fossil-fuel use and industrial processes. The latter is also split into emissions from the energy supply sector (electricity sector and refineries), and direct emissions from fossil-fuel use in energy demand sectors (industry, buildings, transport) (bottom row). Horizontal black lines show the median, boxes show the interquartile range, and whiskers the minimum-maximum range. Icons indicate the four pathway archetypes used in this chapter. In case less than 7 data points are available in a class, the minimum-maximum range and single data points are shown. Kyoto-GHG, emissions in the top panel are aggregated with AR4 GWP-100 and contain CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. NF_3 is typically not reported by IAMs. Scenarios with year-2010 Kyoto-GHG emissions outside

the range assessed by IPCC AR5 WGIII assessed are excluded (IPCC, 2014b)..

2.3.3.2 *Emissions of short-lived climate forcers and fluorinated gases*

SLCFs include shorter-lived GHGs like CH_4 and some HFCs, as well as particles (aerosols), their precursors and ozone precursors. SLCFs are strongly mitigated in 1.5°C pathways as is the case for 2°C pathways (Figure 2.7). SLCF emissions ranges of 1.5°C and 2°C pathway classes strongly overlap, indicating that the main incremental mitigation contribution between 1.5°C and 2°C pathways comes from CO_2 (Luderer et al., 2018; Rogelj et al., 2018). CO_2 and SLCF emissions reductions are connected in situations where SLCF and CO_2 are co-emitted by the same process, for example, with coal-fired power plants (Shindell and Faluvegi, 2010) or within the transport sector (Fuglestvedt et al., 2010). Many CO_2-targeted mitigation measures in industry, transport and agriculture (Sections 2.4.3–4) hence also reduce non-CO_2 forcing (Rogelj et al., 2014b; Shindell et al., 2016).

Despite having a strong warming effect (Myhre et al., 2013; Etminan et al., 2016), current 1.5°C-consistent pathways still project significant emissions of CH_4 by 2050, indicating that only limited mitigation options are included and identified in IAM analyses (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Table 2.A.2). The AFOLU sector contributes an important share of the residual CH_4 emissions until mid-century, with its relative share increasing from slightly below 50% in 2010 to roughly around 55–70% in 2030, and 60–80% in 2050 in 1.5°C-consistent pathways (interquartile range across 1.5°C-consistent pathways for projections). Many of the proposed measures to target CH_4 (Shindell et al., 2012; Stohl et al., 2015) are included in 1.5°C-consistent pathways (Figure 2.7), though not all (Sections 2.3.1.2, 2.4.4, Table 2.A.2). A detailed assessment of measures to further reduce AFOLU CH_4 emissions has not been conducted.

Overall reductions of SLCFs can have effects of either sign on temperature depending on the balance between cooling and warming agents. The reduction in SO_2 emissions is the dominant single effect as it weakens the negative total aerosol forcing. This means that reducing all SLCF emissions to zero would result in a short-term warming, although this warming is unlikely to be more than 0.5°C (Section 2.2 and Figure 1.5 (Samset et al., 2018)). Because of this effect, suggestions have been proposed that target the warming agents only (referred to as short-lived climate pollutants or SLCPs instead of the more general short-lived climate forcers; e.g., Shindell et al., 2012) though aerosols are often emitted in varying mixtures of warming and cooling species (Bond et al., 2013). Black Carbon (BC) emissions reach similar levels across 1.5°C-consistent and 2°C-consistent pathways available in the literature, with interquartile ranges of emissions reductions across pathways of 16–34% and 48–58% in 2030 and 2050, respectively, relative to 2010 (Figure 2.7). Recent studies have identified further reduction potentials for the near term, with global reductions of about 80% being suggested (Stohl et al., 2015; Klimont et al., 2017). Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels, the rapid phase-out of unabated fossil-fuels to avoid CO_2 emissions would also result in removal of these either warming or cooling SLCF air-pollutant species. Furthermore, they are also reduced by efforts to reduce particulate air pollution. For example, year-2050 SO_2 emissions, precursor of sulphate aerosol, in 1.5°C-consistent pathways are about 75–85% lower than their 2010 levels. Some caveats apply, for example, if residential biomass use would be encouraged in industrialised countries in stringent mitigation pathways without appropriate pollution control measures, aerosol concentrations could also increase (Sand et al., 2015; Stohl et al., 2015).

Table 2.4: Emissions in 2030, 2050 and 2100 in 1.5°C and 2°C scenario classes and absolute annual rates of change between 2010–2030, 2020–2030 and 2030–2050, respectively. Values show: median (25th and 75th percentile), across available scenarios. If less than seven scenarios are available (*), the minimum-maximum range is given instead. For the timing of global zero of total net CO_2 and Kyoto-GHG emissions, the interquartile range is given. Kyoto-GHG emissions are aggregated with GWP-100 values from IPCC AR4. 2010 emissions for total net CO_2, CO_2 from fossil-fuel use & industry, and AFOLU CO_2 are estimated at 38.5, 33.4, and 5 $GtCO_2$/yr, respectively (Le Quéré et al., 2018). A difference is reported in estimating the "anthropogenic" sink by countries or the global carbon modelling community (Grassi et al., 2017), and AFOLU CO_2 estimates reported here are thus not necessarily comparable with countries' estimates. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII are excluded (IPCC, 2014b).

	type					Absolute annual change (GtCO2/yr)			Timing of global zero
name	category	count	2030	2050	2100	2010-2030	2020-2030	2030-2050	year
Total CO_2 (net)	Below-1.5°C	5	13 (11 15)	-3 (-11 2)	-8 (-14 -3)	-1.2 (-1.3 -1.0)	-2.5 (-2.8 -1.8)	-0.8 (-1.2 -0.7)	(2037 2054)
	1.5°C-low-OS	37	21 (18 22)	0 (-2 3)	-11 (-14 -8)	-0.8 (-1 -0.7)	-1.7 (-2.3 -1.4)	-1 (-1.2 -0.8)	(2047 2055)
	1.5°C-high-OS	36	29 (26 36)	1 (-1 6)	-14 (-16 -11)	-0.4 (-0.6 0)	-1.1 (-1.5 -0.5)	-1.3 (-1.8 -1.1)	(2049 2059)
	Lower-2°C	67	27 (22 30)	9 (7 13)	-4 (-9 0)	-0.5 (-0.7 -0.3)	-1.2 (-1.9 -0.9)	-0.8 (-1 -0.6)	(2065 2096)
	Higher-2°C	54	33 (31 35)	18 (12 19)	-3 (-11 1)	-0.2 (-0.4 0)	-0.7 (-0.9 -0.5)	-0.8 (-1 -0.6)	(2070 post-2100)
CO_2 from fossil fuels and industry (gross)	Below-1.5°C	5	18 (14 21)	10 (0 21)	8 (0 12)	-0.7 (-1.0 -0.6)	-1.5 (-2.2 -0.9)	-0.4 (-0.7 -0.0)	-
	1.5°C-low-OS	37	22 (19 24)	10 (8 14)	6 (3 8)	-0.5 (-0.6 -0.4)	-1.3 (-1.7 -0.9)	-0.6 (-0.7 -0.5)	-
	1.5°C-high-OS	36	28 (26 37)	13 (12 17)	7 (3 9)	-0.2 (-0.3 0.2)	-0.8 (-1.1 -0.2)	-0.7 (-1 -0.6)	-
	Lower-2°C	67	26 (21 31)	14 (11 18)	8 (4 10)	-0.3 (-0.6 -0.1)	-0.9 (-1.4 -0.6)	-0.6 (-0.7 -0.4)	-
	Higher-2°C	54	31 (29 33)	19 (17 23)	8 (5 11)	-0.1 (-0.2 0.1)	-0.5 (-0.7 -0.2)	-0.6 (-0.7 -0.5)	-
CO_2 from fossil fuels and industry (net)	Below-1.5°C	5	16 (13 18)	1 (0 7)	-3 (-10 0)	-0.8 (-1.0 -0.7)	-1.8 (-2.2 -1.2)	-0.6 (-0.9 -0.5)	-
	1.5°C-low-OS	37	21 (18 22)	3 (-1 6)	-9 (-12 -4)	-0.6 (-0.7 -0.5)	-1.4 (-1.8 -1.1)	-0.8 (-1.1 -0.7)	-
	1.5°C-high-OS	36	27 (25 35)	4 (1 10)	-11 (-13 -7)	-0.3 (-0.3 0.1)	-0.9 (-1.2 -0.3)	-1.2 (-1.5 -0.9)	-
	Lower-2°C	67	26 (21 30)	11 (8 14)	-2 (-5 2)	-0.3 (-0.6 -0.1)	-1 (-1.4 -0.6)	-0.7 (-1 -0.4)	-
	Higher-2°C	54	31 (29 33)	17 (13 19)	-3 (-8 3)	-0.1 (-0.2 0.1)	-0.5 (-0.7 -0.2)	-0.7 (-1 -0.5)	-
CO_2 from AFOLU	Below-1.5°C	5	-2 (-5 0)	-4 (-11 -1)	-4 (-5 -3)	-0.3 (-0.4 -0.2)	-0.5 (-0.8 -0.4)	-0.1 (-0.4 0)	-
	1.5°C-low-OS	37	0 (-1 1)	-2 (-4 -1)	-2 (-4 -1)	-0.2 (-0.3 -0.2)	-0.4 (-0.5 -0.3)	-0.1 (-0.2 -0.1)	-
	1.5°C-high-OS	36	1 (0 3)	-2 (-5 0)	-2 (-5 -1)	-0.1 (-0.3 -0.1)	-0.2 (-0.5 -0.1)	-0.2 (-0.3 0)	-
	Lower-2°C	67	1 (0 2)	-2 (-3 -1)	-2 (-4 -1)	-0.2 (-0.3 -0.1)	-0.3 (-0.4 -0.2)	-0.2 (-0.2 -0.1)	-
	Higher-2°C	54	2 (1 3)	0 (-2 2)	-1 (-4 0)	-0.2 (-0.2 -0.1)	-0.2 (-0.4 -0.1)	-0.1 (-0.1 0)	-
Bioenergy combined with carbon capture and storage (BECCS)	Below-1.5°C	5	0 (-1 0)	-3 (-8 0)	-6 (-13 0)	0 (-0.1 0)	0 (-0.1 0)	-0.2 (-0.4 0)	-
	1.5°C-low-OS	37	0 (-1 0)	-5 (-6 -4)	-12 (-16 -7)	0 (-0.1 0)	0 (-0.1 0)	-0.2 (-0.3 -0.2)	-
	1.5°C-high-OS	36	0 (0 0)	-7 (-9 -4)	-15 (-16 -12)	0 (0 0)	0 (0 0)	-0.3 (-0.4 -0.2)	-
	Lower-2°C	54	0 (0 0)	-4 (-5 -2)	-10 (-12 -7)	0 (0 0)	0 (0 0)	-0.2 (-0.2 -0.1)	-
	Higher-2°C	47	0 (0 0)	-3 (-5 -2)	-11 (-15 -8)	0 (0 0)	0 (0 0)	-0.1 (-0.2 -0.1)	-
Kyoto GHG (AR4) [$GtCO_2e$]	Below-1.5°C	5	22 (21 23)	3 (-3 8)	-3 (-11 3)	-1.4 (-1.5 -1.3)	-2.9 (-3.3 -2.1)	-0.9 (-1.3 -0.7)	(2044 post-2100)
	1.5°C-low-OS	31	28 (26 31)	7 (5 10)	-4 (-8 -2)	-1.1 (-1.2 -0.9)	-2.3 (-2.8 -1.8)	-1.1 (-1.2 -0.9)	(2061 2080)
	1.5°C-high-OS	32	40 (36 49)	8 (6 12)	-9 (-11 -6)	-0.5 (-0.7 0)	-1.3 (-1.8 -0.6)	-1.5 (-2.1 -1.3)	(2058 2067)
	Lower-2°C	59	38 (31 43)	17 (14 20)	3 (0 7)	-0.6 (-1 -0.3)	-1.8 (-2.4 -1.1)	-1 (-1.1 -0.6)	(2099 post-2100)
	Higher-2°C	42	45 (39 49)	26 (23 28)	5 (-5 11)	-0.2 (-0.6 0)	-1 (-1.2 -0.6)	-1 (-1.2 -0.7)	(2085 post-2100)

Emissions of fluorinated gases (IPCC/TEAP, 2005; US EPA, 2013; Velders et al., 2015; Purohit and Höglund-Isaksson, 2017) in 1.5°C-consistent pathways are reduced by roughly 75–80% relative to 2010 levels (interquartile range across 1.5°C-consistent pathways) in 2050, with no clear differences between the classes. Although unabated HFC evolutions have been projected to increase (Velders et al., 2015), the Kigali Amendment recently added HFCs to the basket of gases controlled under the Montreal Protocol (Höglund-Isaksson et al., 2017). As part of the larger group of fluorinated gases, HFCs are also assumed to decline in 1.5°C-consistent pathways. Projected reductions by 2050 of fluorinated gases under 1.5°C-consistent pathways are deeper than published estimates of what a full implementation of the Montreal Protocol's Kigali Amendment would achieve (Höglund-Isaksson et al., 2017), which project roughly a halving of fluorinated gas emissions in 2050 compared to 2010. Assuming the application of technologies that are currently commercially available and at least to a limited extent already tested and implemented, potential fluorinated gas emissions reductions of more than 90% have been estimated (Höglund-Isaksson et al., 2017).

There is a general agreement across 1.5°C-consistent pathways that until 2030 forcing from the warming SLCFs is reduced less strongly than the net cooling forcing from aerosol effects, compared to 2010. As a result, the net forcing contributions from all SLCFs combined are projected to increase slightly by about 0.2–0.4 W/m^2, compared to 2010. Also, by the end of the century, about 0.1–0.3 W/m^2 of SLCF forcing is generally currently projected to remain in 1.5°C-consistent scenarios (Figure 2.8). This is similar to developments in 2°C-consistent pathways (Rose et al., 2014b; Riahi et al., 2017) which show median forcing contributions from these forcing agents that are generally no more than 0.1 W/m^2 higher. Nevertheless, there can be additional gains from targeted deeper reductions of CH_4 emissions and tropospheric ozone precursors, with some scenarios projecting less than 0.1 W/m^2 forcing from SLCFs by 2100.

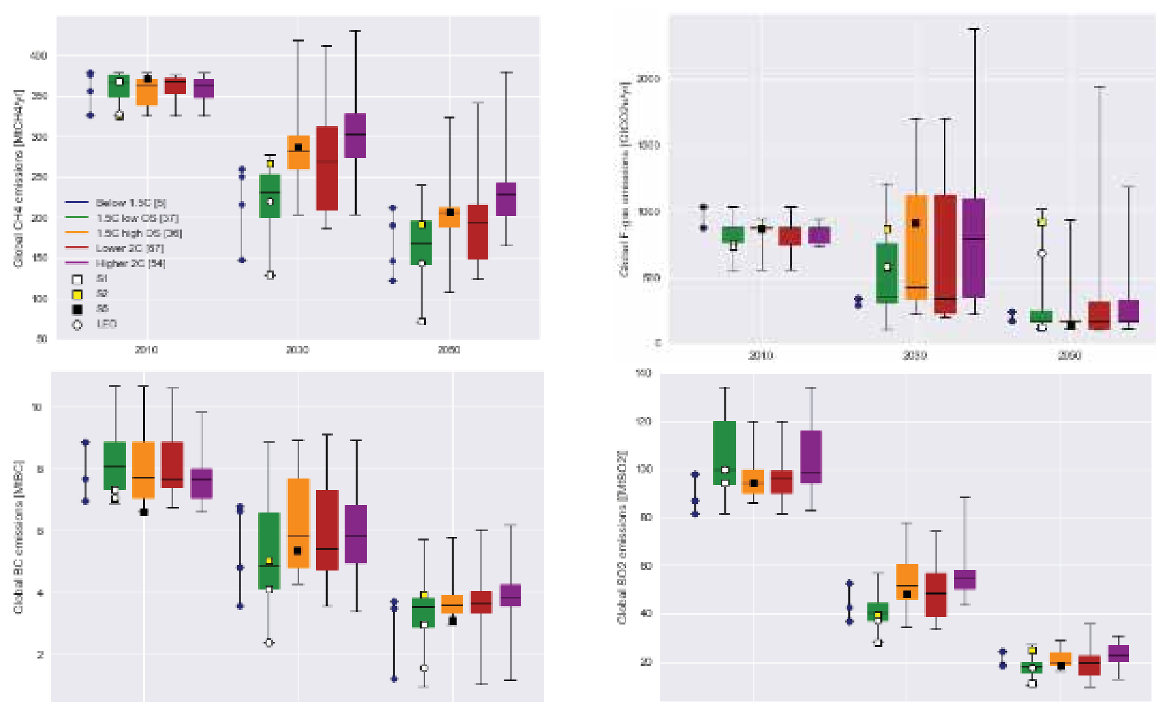

Figure 2.7: Global characteristics of a selection of short-lived non-CO_2 emissions until mid-century for five pathway classes used in this chapter. Data are shown for methane (CH_4), fluorinated gases (F-gas), black carbon (BC), and sulphur dioxide (SO_2) emissions. Boxes with different colours refer to different scenario classes. Icons on top the ranges show four illustrative pathway archetypes that apply different mitigation strategies for limiting warming to 1.5°C. Boxes show the interquartile range, horizontal black lines the median, while whiskers the minimum-maximum range. F-gases are expressed in units of CO_2-equivalence computed with 100-year Global Warming Potentials reported in IPCC AR4.

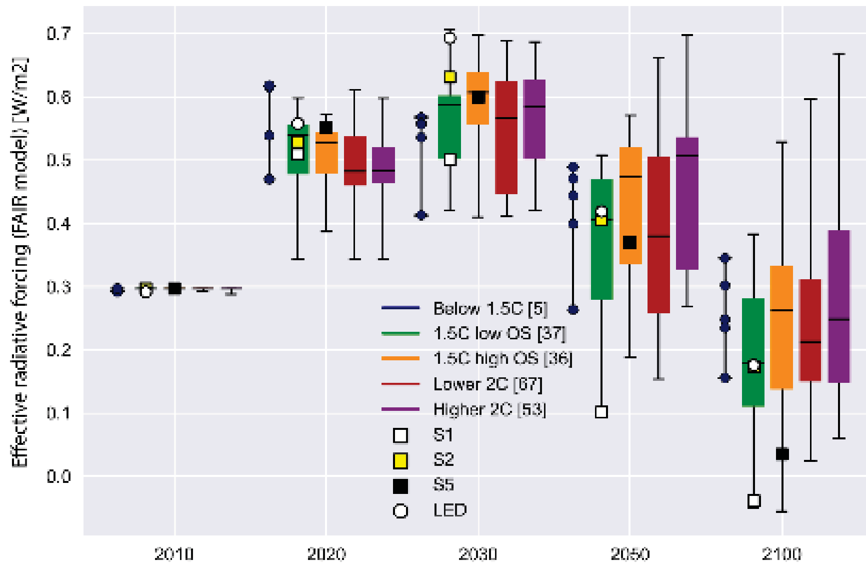

Figure 2.8: Estimated aggregated effective radiative forcing of SLCFs for 1.5°C and 2°C pathway classes in 2010, 2030, 2050, and 2100, as estimated by the FAIR model (Smith et al., 2018). Aggregated SLCF radiative forcing is estimated as the difference between total anthropogenic radiative forcing the sum of CO_2 and N_2O radiative forcing over time and expressed relative to 1750. Symbols indicate the four pathways archetype used in this chapter. Horizontal black lines indicate the median, boxes the interquartile range, and whiskers the minimum-maximum range per pathway class. Due to very few pathways falling into the Below-1.5°C class, only the minimum-maximum is provided here.

2.3.4 CDR in 1.5°C-consistent pathways

Deep mitigation pathways assessed in AR5 showed significant deployment of CDR, in particular through BECCS (Clarke et al., 2014). This has led to increased debate about the necessity, feasibility and desirability of large-scale CDR deployment, sometimes also called 'negative emissions technologies' in the literature (Fuss et al., 2014; Anderson and Peters, 2016; Williamson, 2016; van Vuuren et al., 2017a; Obersteiner et al., 2018). Most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Smith et al., 2015; Dooley and Kartha, 2018). A set of key questions emerge: how strongly do 1.5°C-consistent pathways rely on CDR deployment and what types of CDR measures are deployed at which scale? How does this vary across available 1.5°C-consistent pathways and on which factors does it depend? How does CDR deployment compare between 1.5°C and 2°C-consistent pathways and how does it compare with the findings at the time of the AR5? How does CDR deployment in 1.5°C-consistent pathways relate to questions about availability, policy implementation, and sustainable development implications that have been raised about CDR technologies? The first three questions are assessed in this section with the goal to provide an overview and assessment of CDR deployment in the 1.5°C-consistent pathway literature. The fourth question is only touched upon here and is addressed in greater depth in Section 4.3.7, which assesses the rapidly growing literature on costs, potentials, availability, and sustainability implications of individual CDR measures (Minx et al., 2017, 2018; Fuss et al., 2018; Nemet et al., 2018). In addition, Section 2.3.5 assesses the relationship between delayed mitigation action and increased CDR reliance. CDR deployment is intricately linked to the land-use transformation in 1.5°C-consistent pathways. This transformation is assessed in Section 2.4.4. Bioenergy and BECCS impacts on sustainable land management are further assessed in Section 3.6.2 and Cross-Chapter Box 7 in Chapter 3. Ultimately, a comprehensive assessment of the land implication of land-based CDR measures will be provided in the IPCC AR6 Special Report on Climate Change and Land (SRCCL).

2.3.4.1 CDR technologies and deployment levels in 1.5°C-consistent pathways

A number of approaches to actively remove carbon-dioxide from the atmosphere are increasingly discussed in the literature (Minx et al., 2018) (see also Section 4.3.7). Approaches under consideration include the enhancement of terrestrial and coastal carbon storage in plants and soils such as afforestation and reforestation (Canadell and Raupach, 2008), soil carbon enhancement (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017), and other conservation, restoration, and management options for natural and managed land (Griscom et al., 2017) and coastal ecosystems (McLeod et al., 2011). Biochar sequestration (Woolf et al., 2010; Smith, 2016; Werner et al., 2018) provides an additional route for terrestrial carbon storage. Other approaches are concerned with storing atmospheric carbon dioxide in geological formations. They include the combination of biomass use for energy production with carbon capture and storage (BECCS) (Obersteiner et al., 2001; Keith and Rhodes, 2002; Gough and Upham, 2011) and direct air capture with storage (DACCS) using chemical solvents and sorbents (Zeman and Lackner, 2004; Keith et al., 2006; Socolow et al., 2011). Further approaches investigate the mineralisation of atmospheric carbon dioxide (Mazzotti et al., 2005; Matter et al., 2016) including enhanced weathering of rocks (Schuiling and Krijgsman, 2006; Hartmann et al., 2013; Strefler et al., 2018a). A fourth group of approaches is concerned with the sequestration of carbon dioxide in the oceans, for example by means of ocean alkalinisation (Kheshgi, 1995; Rau, 2011; Ilyina et al., 2013; Lenton et al., 2018). The costs, CDR potential and environmental side effects of several of these measures are increasingly investigated and compared in the literature, but large uncertainties remain, in particular concerning the feasibility and impact of large-scale deployment of CDR measures (The Royal Society, 2009; Smith et al., 2015; Psarras et al., 2017; Fuss et al., 2018) (see Chapter 4.3.7). There are also proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere (Boucher and Folberth, 2010; de Richter et al., 2017), but a broader assessment of their effectiveness, cost, and sustainability impacts is lacking to date.

Only some of these approaches have so far been considered in IAMs (see Section 2.3.1.2). The mitigation scenario literature up to AR5 mostly included BECCS and to a more limited extent afforestation and reforestation (Clarke et al., 2014). Since then, some 2°C and 1.5°C-consistent pathways including additional CDR measures such as DACCS (Chen and Tavoni, 2013; Marcucci et al., 2017; Lehtilä and Koljonen, 2018; Strefler et al., 2018b) and soil carbon sequestration (Frank et al., 2017) have become available. Other, more speculative approaches, in particular ocean-based CDR and removal of non-CO_2 gases, have not yet been taken up by the literature on mitigation pathways. See Annex 2.A.2 for an overview on the coverage of CDR measures in models which contributed pathways to this assessment. Chapter 4.3.7 assesses the potential, costs, and sustainability implications of the full range of CDR measures.

Integrated assessment modelling has not yet explored land conservation, restoration and management options to remove carbon dioxide from the atmosphere in sufficient depth, despite land management having a potentially considerable impact on the terrestrial carbon stock (Erb et al., 2018). Moreover, associated CDR measures have low technological requirements, and come with potential environmental and social co-benefits (Griscom et al., 2017). Despite the evolving capabilities of IAMs in accounting for a wider range of CDR measures, 1.5°C-consistent pathways assessed here continue to predominantly rely on BECCS and afforestation / reforestation (See Annex 2.A.2). However, IAMs with spatially explicit land-use modelling include a full accounting of land-use change emissions comprising carbon stored in the terrestrial biosphere and soils. Net CDR in the AFOLU sector, including but not restricted to afforestation and reforestation, can thus in principle be inferred by comparing AFOLU CO_2 emissions between a baseline scenario and a 1.5°C-consistent pathway from the same model and study. However, baseline LUC emissions cannot only be reduced by CDR in the AFOLU sector, but also by measures to reduce deforestation and preserve land carbon stocks. The pathway literature and pathway data available to this assessment do not yet allow to separate the two contributions. As a conservative approximation, the additional net negative AFOLU CO_2 emissions below the baseline are taken as a proxy for AFOLU CDR in this assessment. Because this does not include CDR that was deployed before reaching net zero AFOLU emissions, this approximation is a lower-bound for terrestrial CDR in the AFOLU sector (including the factors that lead to net negative LUC emissions).

The scale and type of CDR deployment in 1.5°C-consistent pathways varies widely (Figure 2.9 and 2.10). Overall CDR deployment over the 21st century is substantial in most of the pathways, and deployment levels cover a wide range (770 [260-1170] $GtCO_2$, for median and 5th–95th percentile range). Both BECCS (560 [0 to 1000] $GtCO_2$) and AFOLU CDR measures including afforestation and reforestation (200 [0-550] $GtCO_2$)

can play a major role[4], but for both cases pathways exist where they play no role at all. This shows the flexibility in substituting between individual CDR measures, once a portfolio of options becomes available. The high end of the CDR deployment range is populated by high overshoot pathways, as illustrated by pathway archetype S5 based on SSP5 (fossil-fuelled development, see Section 2.3.1.1) and characterized by very large BECCS deployment to return warming to 1.5°C by 2100 (Kriegler et al., 2017). In contrast, the low end is populated with pathways with no or limited overshoot that limit CDR to in the order of 100–200 $GtCO_2$ over the 21st century coming entirely from terrestrial CDR measures with no or small use of BECCS. These are pathways with very low energy demand facilitating the rapid phase-out of fossil fuels and process emissions that exclude BECCS and CCS use (Grubler et al., 2018) and/or pathways with rapid shifts to sustainable food consumption freeing up sufficient land areas for afforestation and reforestation (Haberl et al., 2011; van Vuuren et al., 2018). Some pathways uses neither BECCS nor afforestation but still rely on CDR through considerable net negative emissions in the AFOLU sector around mid-century (Holz et al., 2018b). We conclude that the role of BECCS as dominant CDR measure in deep mitigation pathways has been reduced since the time of the AR5. This is related to three factors: a larger variation of underlying assumptions about socio-economic drivers (Riahi et al., 2017; Rogelj et al., 2018) and associated energy (Grubler et al., 2018) and food demand (van Vuuren et al., 2018); the incorporation of a larger portfolio of mitigation and CDR options (Liu et al., 2017; Marcucci et al., 2017; Grubler et al., 2018; Lehtilä and Koljonen, 2018; van Vuuren et al., 2018); and targeted analysis of deployment limits for (specific) CDR measures (Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b) including on the availability of bioenergy (Bauer et al., 2018), CCS (Krey et al., 2014a; Grubler et al., 2018) and afforestation (Popp et al., 2014b, 2017). As additional CDR measures are being built into IAMs, the prevalence of BECCS is expected to be further reduced.

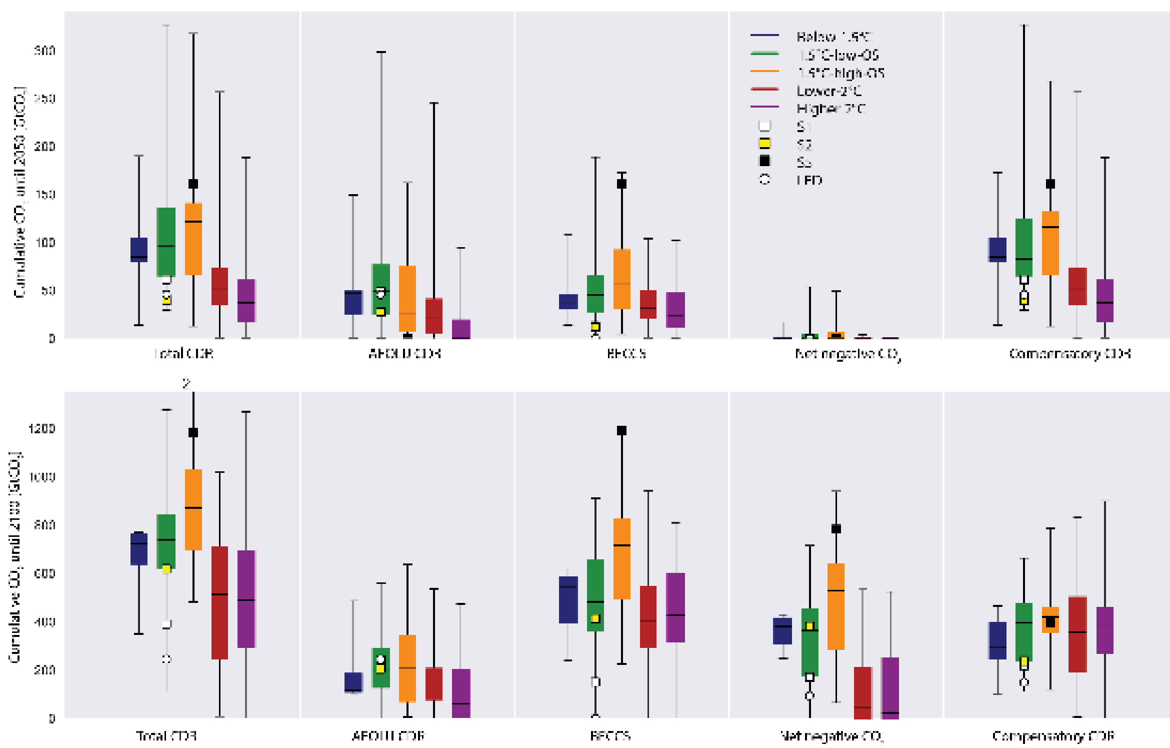

Figure 2.9: Cumulative CDR deployment in 1.5°C-consistent pathways in the literature as reported in the database collected for this assessment. Total CDR comprises all forms of CDR, including AFOLU CDR and BECCS, and in a few pathways other CDR measures like DACCS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not result in active removal of CO_2 from the atmosphere). AFOLU CDR has not been reported directly and is hence represented by means of a proxy: the additional amount of net negative CO_2 emissions in the AFOLU sector compared to a baseline scenario (see text for a discussion). 'Compensate CO_2' depicts the cumulative amount of CDR that is used to neutralize concurrent residual CO_2 emissions. 'Net negative CO_2' describes the additional

[4] FOOTNOTE: The median and percentiles of the sum of two quantities is in general not equal to the sum of the medians of the two quantitites.

amount of CDR that is used to produce net negative emissions, once residual CO_2 emissions are neutralized. The two quantities add up to total CDR for individual pathways (not for percentiles and medians, see Footnote 4).

As discussed in Section 2.3.2, CDR can be used in two ways: (i) to move more rapidly towards the point of carbon neutrality and maintain it afterwards to stabilize global-mean temperature rise, and (ii) to produce net negative emissions drawing down anthropogenic CO_2 in the atmosphere to enable temperature overshoot by declining global-mean temperature rise after its peak (Kriegler et al., 2018a; Obersteiner et al., 2018). Both uses are important in 1.5°C-consistent pathways (Figure 2.9). Because of the tighter remaining 1.5°C carbon budget, and because many pathways in the literature do not restrict exceeding this budget prior to 2100, the relative weight of the net negative emissions component of CDR increases compared to 2°C-consistent pathways. The amount of compensatory CDR remains roughly the same over the century. This is the net effect of stronger deployment of compensatory CDR until mid-century to accelerate the approach to carbon neutrality and less compensatory CDR in the second half of the century due to deeper mitigation of end-use sectors in 1.5°C-consistent pathways (Luderer et al., 2018). Comparing median levels, end-of-century net cumulative CO_2 emissions are roughly 600 $GtCO_2$ smaller in 1.5°C compared to 2°C-consistent pathways, with approximately two thirds coming from further reductions of gross CO_2 emissions and the remaining third from increased CDR deployment. As a result, total CDR deployment in the combined body of 1.5°C-consistent pathways is often larger than in 2°C-consistent pathways (Figure 2.9), but with marked variations in each pathway class.

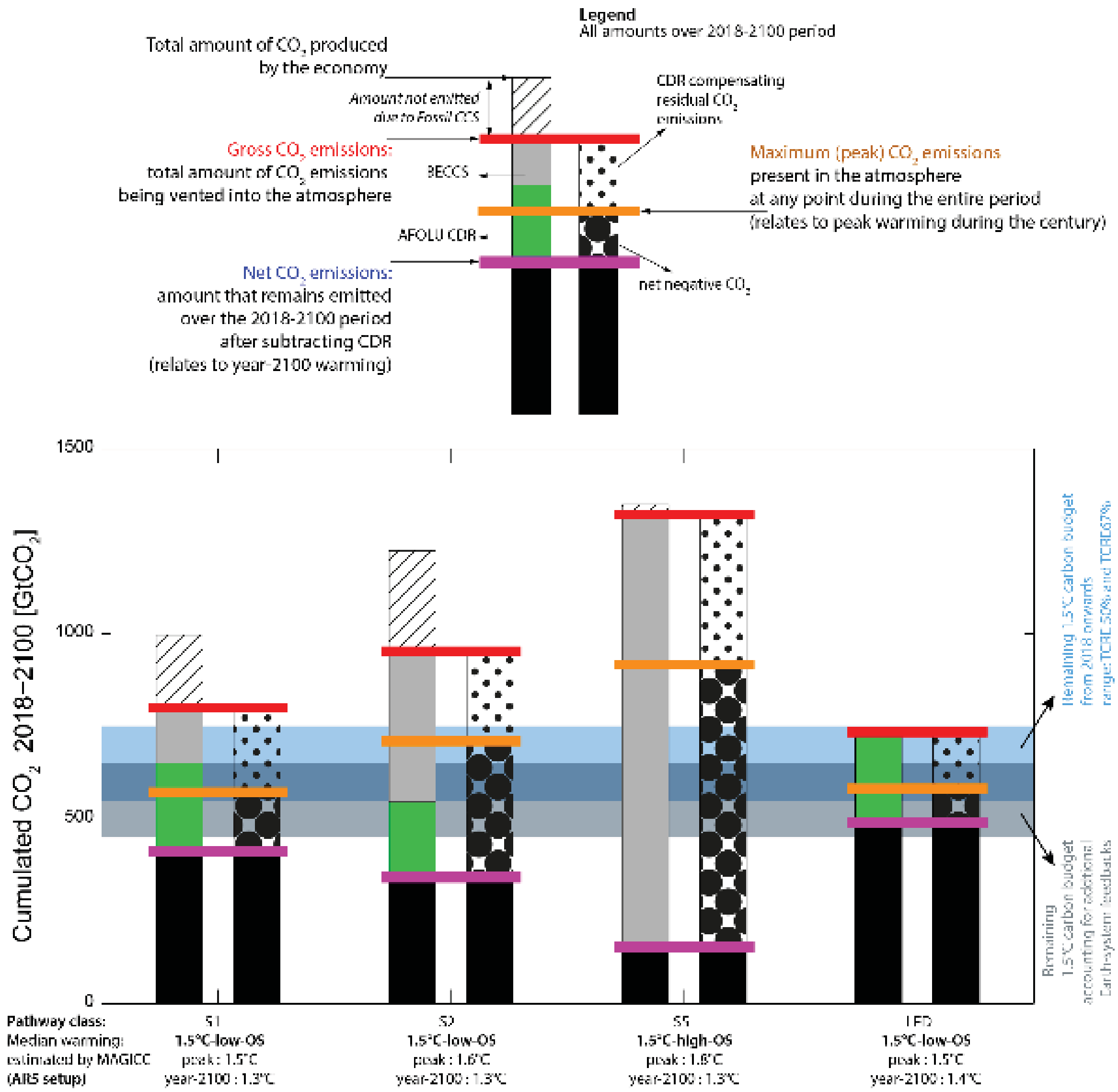

Figure 2.10: Accounting of cumulative CO_2 emissions for the four 1.5°C-consistent pathway archetypes. See top panel for explanation of the barplots. Total CDR is the difference between gross (red horizontal bar) and net (purple horizontal bar) cumulative CO_2 emissions over the period 2018–2100. Total CDR is the sum of the BECCS (grey) and AFOLU CDR (green) contributions. Cumulative net negative emissions are the difference between peak (orange horizontal bar) and net (purple) cumulative CO_2 emissions. The blue shaded area depicts the estimated range of the remaining carbon budget for a two-in-three to one-in-two chance of staying below1.5°C. The grey shaded area depicts the range when accounting for additional Earth-system feedbacks. These remaining carbon budgets have been adjusted for the difference in starting year compared to Table 2.2

Ramp-up rates of individual CDR measures in 1.5°C-consistent pathways are provided in Table 2.4. BECCS deployment is still limited in 2030, but ramped up to median levels of 3 (Below-1.5°C), 5 (1.5°C-low-OS) and 7 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2050, and to 6 (Below-1.5°C), 12 (1.5°C-low-OS) and 15 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2100, respectively. Net CDR in the AFOLU sector reaches slightly lower levels in 2050, and stays more constant until 2100, but data reporting limitations prevent a more quantitative assessment here. In contrast to BECCS, AFOLU CDR is more strongly deployed in non-overshoot than overshoot pathways. This indicates differences in the timing of the two CDR approaches. Afforestation is scaled up until around mid-century, when the time of carbon neutrality is reached in 1.5°C-consistent pathways, while BECCS is projected to be used predominantly in the 2nd half of the century. This reflects that afforestation is a readily available CDR technology, while BECCS is more costly and much less mature a technology. As a result, the two options contribute differently to compensating concurrent CO_2 emissions (until 2050) and to producing net negative CO_2 emissions (post-2050). BECCS deployment is particularly strong in pathways with high overshoots but could equally feature in pathways with a low temperature peak but a fast temperature decline thereafter (see Figure 2.1). Annual deployment levels until mid-century are not found to be significantly different between 2°C-consistent pathways and 1.5°C-consistent pathways with no or low overshoot. This suggests similar implementation challenges for ramping up CDR deployment at the rates projected in the pathways (Honegger and Reiner, 2018; Nemet et al., 2018). The feasibility and sustainability of upscaling CDR at these rates is assessed in Chapter 4.3.7.

Concerns have been raised that building expectations about large-scale CDR deployment in the future can lead to an actual reduction of near-term mitigation efforts (Geden, 2015; Anderson and Peters, 2016; Dooley and Kartha, 2018). The pathway literature confirms that CDR availability influences the shape of mitigation pathways critically (Krey et al., 2014a; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b). Deeper near-term emissions reductions are required to reach the 1.5°C-2°C target range, if CDR availability is constrained. As a result, the least-cost benchmark pathways to derive GHG emissions gap estimates (UNEP, 2017) are dependent on assumptions about CDR availability. Using GHG benchmarks in climate policy makes implicit assumptions about CDR availability (Fuss et al., 2014; van Vuuren et al., 2017a). At the same time, the literature also shows that rapid and stringent mitigation as well as large-scale CDR deployment occur simultaneously in 1.5°C pathways due to the tight remaining carbon budget (Luderer et al., 2018). Thus, an emissions gap is identified even for high CDR availability (Strefler et al., 2018b), contradicting a wait-and-see approach. There are significant trade-offs between near-term action, overshoot and reliance on CDR deployment in the long-term which are assessed in Section 2.3.5.

Box 2.1: Bioenergy and BECCS deployment in integrated assessment modelling

Bioenergy can be used in various parts of the energy sector of IAMs, including for electricity, liquid fuel, biogas, and hydrogen production. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonisation of energy use (Klein et al., 2014; Krey et al., 2014a; Rose et al., 2014a; Bauer et al., 2017, 2018). Most bioenergy technologies in IAMs are also available in combination with CCS (BECCS). Assumed capture rates differ between technologies, for example, about 90% for electricity and hydrogen production, and about 40-50% for liquid fuel production. Decisions about bioenergy deployment in IAMs are based on economic considerations to stay within a carbon budget that is consistent with a long-term climate goal. IAMs consider both the value of bioenergy in the energy system and the value of BECCS in removing CO_2 from the atmosphere. Typically, if bioenergy is strongly limited, BECCS technologies with high capture rates are favoured. If bioenergy is plentiful IAMs tend to choose biofuel technologies with lower capture rate, but high value for replacing fossil fuels in transport (Kriegler et al., 2013a; Bauer et al., 2018). Most bioenergy use in IAMS is combined with CCS if available (Rose et al., 2014a). If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for the energy transformation (Bauer et al., 2018). As land impacts are tied to bioenergy use, the exclusion of BECCS from the mitigation portfolio, will not automatically remove the trade-offs with food, water and other sustainability objectives due to the continued and potentially increased use of bioenergy.

IAMs assume bioenergy to be supplied mostly from second generation biomass feedstocks such as dedicated cellulosic crops (for example Miscanthus or Poplar) as well as agricultural and forest residues. Detailed process IAMs include land-use models that capture competition for land for different uses (food, feed, fiber, bioenergy, carbon storage, biodiversity protection) under a range of dynamic factors including socio-economic drivers, productivity increases in crop and livestock systems, food demand, and land, environmental, biodiversity, and carbon policies. Assumptions about these factors can vary widely between different scenarios (Calvin et al., 2014; Popp et al., 2017; van Vuuren et al., 2018). IAMs capture a number of potential environmental impacts from bioenergy production, in particular indirect land-use change emissions from land conversion and nitrogen and water use for bioenergy production (Kraxner et al., 2013; Bodirsky et al., 2014; Bonsch et al., 2014; Obersteiner et al., 2016; Humpenöder et al., 2017). Especially the impact of bioenergy production on soil degradation is an area of active IAM development and was not comprehensively accounted for in the mitigation pathways assessed in this report (but is, for example, in (Frank et al., 2017)). Whether bioenergy has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Haberl et al., 2013; Erb et al., 2016b; Obersteiner et al., 2016; Humpenöder et al., 2017). Here IAMs often make idealized assumptions about effective land management such as full protection of the land carbon stock by conservation measures and a global carbon price, respectively, but also variations on these assumptions have been explored (Calvin et al., 2014; Popp et al., 2014a)).

2.3.4.2 *Sustainability implications of CDR deployment in 1.5°C-consistent pathways*

Strong concerns about the sustainability implications of large-scale CDR deployment in deep mitigation pathways have been raised in the literature (Williamson and Bodle, 2016; Boysen et al., 2017b; Dooley and Kartha, 2018; Heck et al., 2018), and a number of important knowledge gaps have been identified (Fuss et al., 2016). An assessment of the literature on implementation constraints and sustainable development implications of CDR measures is provided in Section 4.3.7 and the Cross-chapter Box 7 in Chapter 3. Potential environmental side effects as initial context for the discussion of CDR deployment in 1.5°C-consistent pathways are provided in this section. Section 4.3.7 then contrasts CDR deployment in 1.5°C-consistent pathways with other branches of literature on limitations of CDR. Integrated modelling aims to explore a range of developments compatible with specific climate goals and often does not include the full set of broader environmental and societal concerns beyond climate change. This has given rise to the concept of sustainable development pathways (van Vuuren et al., 2015) (Cross-Chapter Box 1 in Chapter 1), and there is an increasing body of work to extend integrated modelling to cover a broader range of sustainable development goals (Section 2.6). However, only some of the available 1.5°C-consistent pathways were developed within a larger sustainable development context (Bertram et al., 2018; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018). As discussed in Section 2.3.4.1, those pathways are characterized by low energy and/or food demand effectively limiting fossil-fuel substitution and alleviating land competition, respectively. They also include regulatory policies for deepening early action and ensuring environmental protection (Bertram et al., 2018). Overall sustainability implications of 1.5°C-consistent pathways are assessed in Section 2.5.3 and Section 5.4.

Individual CDR measures have different characteristics and therefore would carry different risks for their sustainable deployment at scale (Smith et al., 2015). Terrestrial CDR measures, BECCS and enhanced weathering of rock powder distributed on agricultural lands require land. Those land-based measures could have substantial impacts on environmental services and ecosystems (Smith and Torn, 2013; Boysen et al., 2016; Heck et al., 2016; Krause et al., 2017) (Cross-Chapter Box 7 in Chapter 3). Measures like afforestation and bioenergy with and without CCS that directly compete with other land uses could have significant impacts on agricultural and food systems (Creutzig et al., 2012, 2015; Calvin et al., 2014; Popp et al., 2014b, 2017; Kreidenweis et al., 2016; Boysen et al., 2017a; Frank et al., 2017; Humpenöder et al., 2017; Stevanović et al., 2017; Strapasson et al., 2017). BECCS using dedicated bioenergy crops could substantially increase agricultural water demand (Bonsch et al., 2014; Séférian et al., 2018) and nitrogen fertilizer use (Bodirsky et al., 2014). DACCS and BECCS rely on CCS and would require safe storage space in geological formations, including management of leakage risks (Pawar et al., 2015) and induced seismicity (Nicol et al., 2013). Some approaches like DACCS have high energy demand (Socolow et al., 2011). Most of the CDR measures currently discussed could have significant impacts on either land, energy, water, or nutrients if deployed at scale (Smith et al., 2015). However, actual trade-offs depend on a multitude factors (Haberl et al., 2011; Erb et al., 2012; Humpenöder et al., 2017), including the modalities of CDR deployment (e.g., on marginal vs. productive land) (Bauer et al., 2018), socio-economic developments (Popp et al., 2017), dietary choices (Stehfest et al., 2009; Popp et al., 2010; van Sluisveld et al., 2016; Weindl et al., 2017; van Vuuren et al., 2018), yield increases, livestock productivity and other advances in agricultural technology (Havlik et al., 2013; Valin et al., 2013; Havlík et al., 2014; Weindl et al., 2015; Erb et al., 2016b), land policies (Schmitz et al., 2012; Calvin et al., 2014; Popp et al., 2014a) and governance of land use (Unruh, 2011; Buck, 2016; Honegger and Reiner, 2018).

Figure 2.11 shows the land requirements for BECCS and afforestation in the selected 1.5°C-consistent pathway archetypes, including the LED (Grubler et al., 2018) and S1 pathways (Fujimori, 2017; Rogelj et al., 2018) following a sustainable development paradigm. As discussed, these land-use patterns are heavily influenced by assumptions about, inter alia, future population levels, crop yields, livestock production systems, and food and livestock demand, which all vary between the pathways (Popp et al., 2017) (Section 2.3.1.1). In pathways that allow for large-scale afforestation in addition to BECCS, land demand for afforestation can be larger than for BECCS (Humpenöder et al., 2014). This follows from the assumption in the modelled pathways that, unlike bioenergy crops, forests are not harvested to allow unabated carbon storage on the same patch of land. If wood harvest and subsequent processing or burial are taken into account, this finding can change. There are also synergies between the various uses of land, which are not reflected in the depicted pathways. Trees can grow on agricultural land (Zomer et al., 2016) and harvested wood can be used with BECCS and pyrolysis systems (Werner et al., 2018). The pathways show a very substantial land demand for the two CDR measures combined, up to the magnitude of the current global cropland area. This is achieved in IAMs in particular by a conversion of pasture land freed by intensification of livestock production systems, pasture intensification and/or demand changes (Weindl et al., 2017), and to more limited extent cropland for food production, as well as expansion into natural land. However, pursuing such large scale changes in land use would pose significant food supply, environmental and governance challenges, concerning both land management and tenure (Unruh, 2011; Erb et al., 2012, 2016b; Haberl et al., 2013; Haberl, 2015; Buck, 2016), particularly if synergies between land uses, the relevance of dietary changes for reducing land demand, and co-benefits with other sustainable development objectives are not fully recognized. A general discussion of the land-use transformation in 1.5°C-consistent pathways is provided in Section 2.4.4.

An important consideration for CDR which moves carbon from the atmosphere to the geological, oceanic or terrestrial carbon pools is the permanence of carbon stored in these different pools (Matthews and Caldeira, 2008; NRC, 2015; Fuss et al., 2016; Jones et al., 2016) (see also Section 4.3.7 for a discussion). Terrestrial carbon can be returned to the atmosphere on decadal timescales by a variety of mechanisms such as soil degradation, forest pest outbreaks and forest fires, and therefore requires careful consideration of policy frameworks to manage carbon storage, e.g., in forests (Gren and Aklilu, 2016). There are similar concerns about outgassing of CO_2 from ocean storage (Herzog et al., 2003), unless it is transformed to a substance that does not easily exchange with the atmosphere, e.g., ocean alkalinity or buried marine biomass (Rau, 2011). Understanding of the assessment and management of the potential risk of CO_2 release from geological storage of CO_2 has improved since the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) with experience and the development of management practices in geological storage projects, including risk management to prevent sustentative leakage (Pawar et al., 2015). Estimates of leakage risk have been updated to include scenarios of unregulated drilling and limited wellbore integrity (Choi et al., 2013), finding ca. 70% of stored CO_2 still retained after 10,000 years in these circumstances (Alcalde et al., 2018). The literature on the potential environmental impacts from the leakage of CO_2 – and approaches to minimize these impacts should a leak occur – has also grown and is reviewed by Jones et al. (2015). To the extent non-permanence of terrestrial and geological carbon storage is driven by socio-economic and political factors, it has parallels to questions of fossil-fuel reservoirs remaining in the ground (Scott et al., 2015).

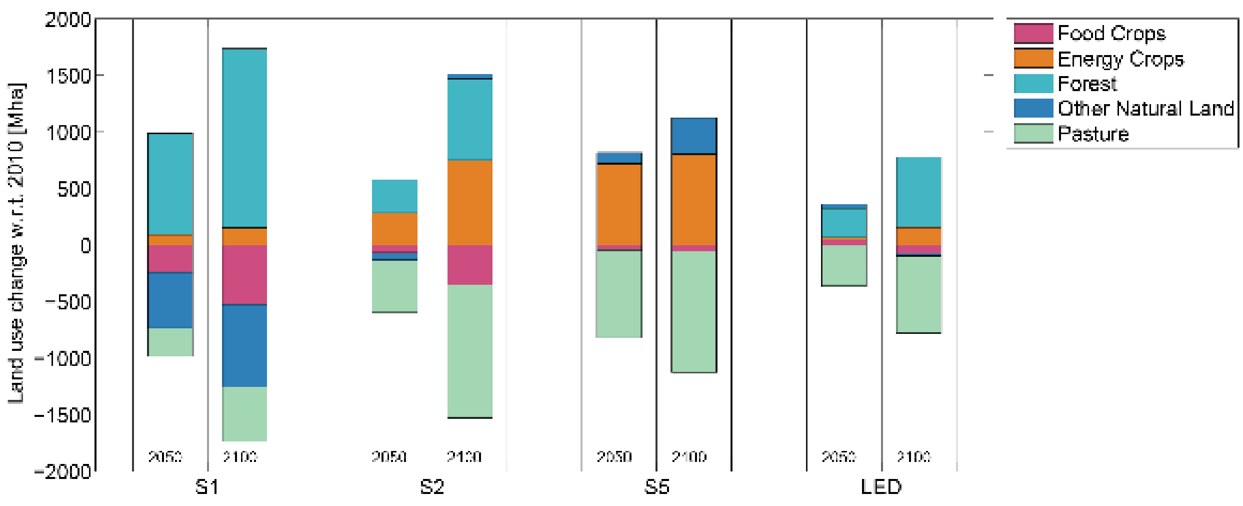

Figure 2.11: Land-use changes in 2050 and 2100 in the illustrative 1.5°C-consistent pathway archetypes (Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Grubler et al., 2018; Rogelj et al., 2018).

2.3.5 *Implications of near-term action in 1.5°C-consistent pathways*

Less CO_2 emission reductions in the near term imply steeper and deeper reductions afterwards (Riahi et al., 2015; Luderer et al., 2016a). This is a direct consequence of the quasi-linear relationship between the total cumulative amount of CO_2 emitted into the atmosphere and global mean temperature rise (Matthews et al., 2009; Zickfeld et al., 2009; Collins et al., 2013; Knutti and Rogelj, 2015). Besides this clear geophysical trade-off over time, delaying GHG emissions reductions over the coming years also leads to economic and institutional lock-in into carbon-intensive infrastructure, that is, the continued investment in and use of carbon-intensive technologies that are difficult or costly to phase-out once deployed (Unruh and Carrillo-Hermosilla, 2006; Jakob et al., 2014; Erickson et al., 2015; Steckel et al., 2015; Seto et al., 2016; Michaelowa et al., 2018). Studies show that to meet stringent climate targets despite near-term delays in emissions reductions, models prematurely retire carbon-intensive infrastructure, in particular coal without CCS (Bertram et al., 2015a; Johnson et al., 2015). The AR5 reports that delaying mitigation action leads to substantially higher rates of emissions reductions afterwards, a larger reliance on CDR technologies in the long term, and higher transitional and long-term economic impacts (Clarke et al., 2014). The literature mainly focuses on delayed action until 2030 in the context of meeting a 2°C goal (den Elzen et al., 2010; van Vuuren and Riahi, 2011; Kriegler et al., 2013b; Luderer et al., 2013, 2016a; Rogelj et al., 2013b; Riahi et al., 2015; OECD/IEA and IRENA, 2017). However, because of the smaller carbon budget consistent with limiting warming to 1.5°C and the absence of a clearly declining long-term trend in global emissions to date, these general insights apply equally or even more so to the more stringent mitigation context of 1.5°C-consistent pathways. This is further supported by estimates of committed emissions due to fossil fuel-based infrastructure (Seto et al., 2016; Edenhofer et al., 2018).

All available 1.5°C pathways that explore consistent mitigation action from 2020 onwards peak global Kyoto-GHG emissions in the next decade and already decline Kyoto-GHG emissions to below 2010 levels by 2030. The near-term emissions development in these pathways can be compared with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement (Figure 2.12). Altogether, these NDCs are assessed to result in global Kyoto-GHG emissions on the order of 50–58 $GtCO_2e\ yr^{-1}$ in 2030 (for example, den Elzen et al., 2016; Fujimori et al., 2016; UNFCCC, 2016; Rogelj et al., 2017; Rose et al., 2017b; Benveniste et al., 2018; Vrontisi et al., 2018), see Cross-Chapter Box 11 in Chapter 4 for detailed assessment). In contrast, 1.5°C-consistent pathways available to this assessment show an interquartile range of about 26–38 (median 31) $GtCO_2e\ yr^{-1}$ in 2030, reducing to 26–31 (median 28) $GtCO_2e\ yr^{-1}$ if only pathways with low overshoot are taken into account[5], and still lower if pathways without overshoot are considered (Table 2.4, Section 2.3.3). Published estimates of the emissions gap between conditional NDCs and 1.5°C-consistent pathways in 2030 range from 16 (14–22) $GtCO_2e\ yr^{-1}$ (UNEP, 2017) for a greater than one-in-to chance of limiting warming below 1.5°C in 2100 to 25 (19–29) $GtCO_2e\ yr^{-1}$ (Vrontisi et al., 2018) for a greater than two-in-three chance of meeting the 1.5°C limit.

The later emissions peak and decline, the more CO_2 will have accumulated in the atmosphere. Peak cumulated CO_2 emissions and consequently also peak temperatures increase with 2030 emissions levels (Figure 2.12). Current NDCs (Cross-Chapter Box 11 in Chapter 4) are estimated to lead to CO_2 emissions of about 400–560 $GtCO_2$ from 2018 to 2030 (Rogelj et al., 2016a). Available 1.5°C- and 2°C-consistent pathways with 2030 emissions in the range estimated for the NDCs rely on an assumed swift and widespread deployment of CDR after 2030, and show peak cumulative CO_2 emissions from 2018 of about 800–1000 $GtCO_2$, above the remaining carbon budget for a one-in-two chance of remaining below 1.5°C. These emissions reflect that no pathway is able to project a phase out of CO_2 emissions starting from year-2030 NDC levels of about 40 $GtCO_2\ yr^{-1}$ (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero in less than ca. 15 years. Based on the implied emissions until 2030, the high challenges of the assumed post-2030 transition, and the assessment of carbon budgets in Section 2.2.2, global warming is assessed to exceed 1.5°C if emissions stay at the levels implied by the NDCs until 2030 (Figure 2.12). The chances of remaining below 1.5°C in these circumstances remain conditional upon geophysical properties that are uncertain, but these

[5] FOOTNOTE: Note that aggregated Kyoto-GHG emissions implied by the NDCs from Cross-Chapter Box 4.3 and Kyoto-GHG ranges from the pathway classes in Chapter 2 are only approximately comparable, because this chapter applies GWP-100 values from the IPCC Fourth Assessment Report while the NDC Cross-Chapter Box 4.3 applies GWP-100 values from the IPCC Second Assessment Report. At a global scale, switching between GWP-100 values of the Second to the Fourth IPCC Assessment Report would result in an increase in estimated aggregated Kyoto-GHG emissions of about no more than 3% in 2030 (UNFCCC, 2016).

Earth system response uncertainties would have to serendipitously align beyond current median estimates in order for current NDCs to become consistent with limiting warming to 1.5°C.

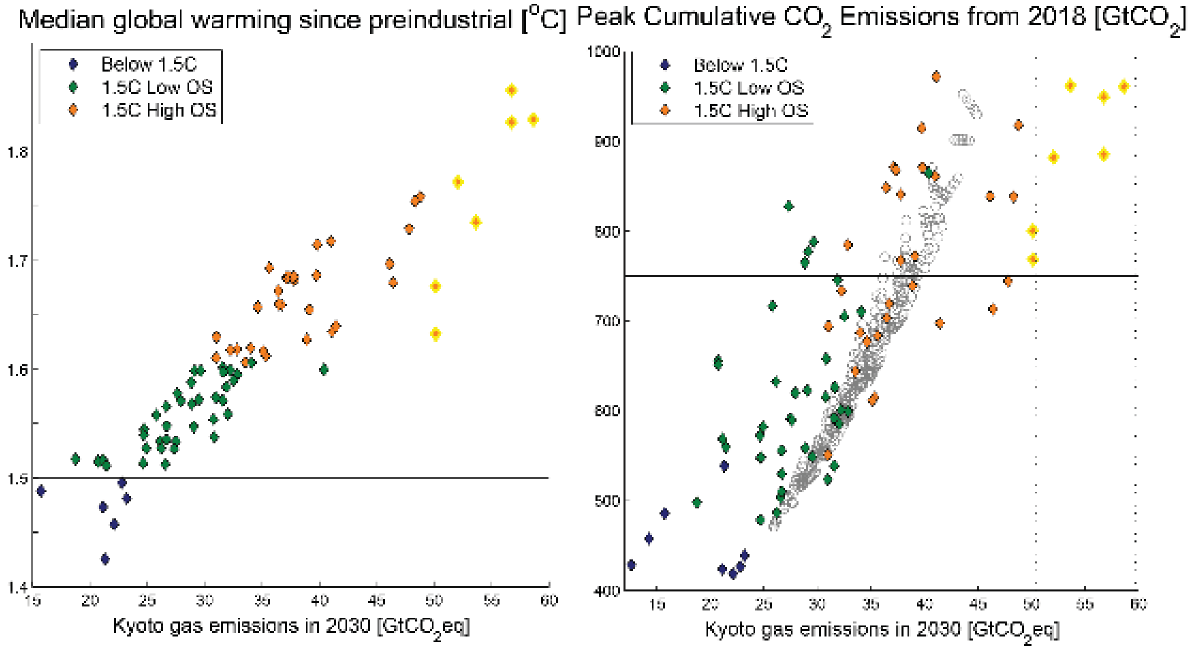

Figure 2.12: Median global warming estimated by MAGICC (left panel) and peak cumulative CO_2 emissions (right panel) in 1.5°C-consistent pathways in the SR1.5 scenario database as a function of CO_2-equivalent emissions (based on AR4 GWP-100) of Kyoto-GHGs in 2030. Pathways that were forced to go through the NDCs or a similarly high emissions point in 2030 by design are highlighted by yellow marker edges (see caption of Figure 2.13 and text for further details on the design of these pathways). The NDC range of global Kyoto-GHG emissions in 2030 assessed in Cross-Chapter Box 11 in Chapter 4 is shown by black dotted lines (adjusted to AR4 GWPs for comparison). As a second line of evidence, peak cumulative CO_2 emissions derived from a 1.5°C pathway sensitivity analysis (Kriegler et al., 2018a) are shown by grey circles in the right-hand panel. Numbers show gross fossil-fuel and industry emissions of the sensitivity cases increased by assumptions about the contributions from AFOLU (5 $GtCO_2$ yr^{-1} until 2020, followed by a linear phase out until 2040) and non-CO_2 Kyoto-GHGs (median non-CO_2 contribution from 1.5°C-consistent pathways available in the database: 10 $GtCO_2e$ yr^{-1} in 2030), and reduced by assumptions about CDR deployment until the time of net zero CO_2 emissions (limiting case for CDR deployment assumed in (Kriegler et al., 2018a) (logistic growth to 1, 4, 10 $GtCO_2$ yr^{-1} in 2030, 2040, and 2050, respectively, leading to approx. 100 $GtCO_2$ CDR by mid-century).

It is unclear whether following NDCs until 2030 would still allow global mean temperature to return to 1.5°C by 2100 after a temporary overshoot, due to the uncertainty associated with the Earth system response to net negative emissions after a peak (Section 2.2). Available IAM studies are working with reduced-form carbon cycle-climate models like MAGICC which assume a largely symmetric Earth-system response to positive and net negative CO_2 emissions. The IAM findings on returning warming to 1.5°C from NDCs after a temporary temperature overshoot are hence all conditional on this assumption. Two types of pathways with 1.5°C-consistent action starting in 2030 have been considered in the literature (Luderer et al., 2018) (Figure 2.13): pathways aiming to obtain the same end-of-century carbon budget despite higher emissions until 2030, and pathways assuming the same mitigation stringency after 2030 (approximated by using the same global price of emissions as found in least-cost pathways starting from 2020). An IAM comparison study found increasing challenges to implement pathways with the same end-of-century 1.5°C-consistent carbon budgets after following NDCs until 2030 (ADVANCE) (Luderer et al., 2018). The majority of model experiments (four out of seven) failed to produce NDC pathways that would return cumulative CO_2 emissions over the 2016–2100 period to 200 $GtCO_2$, indicating limitations to the availability and timing of CDR. The few such pathways that were identified show highly disruptive features in 2030 (including abrupt transitions from moderate to very large emissions reduction and low carbon energy deployment rates) indicating a high risk that the required post-2030 transformations are too steep and abrupt to be achieved by the mitigation measures in the models (*high confidence*). NDC pathways aiming for a cumulative 2016–2100 CO_2 emissions budget of 800 $GtCO_2$ were more readily obtained (Luderer et al., 2018), and some were classified as 1.5°C-high-OS pathways in this assessment (Section 2.1).

NDC pathways that apply a post-2030 price of emissions after 2030 as found in least-cost pathways starting from 2020 show infrastructural carbon lock-in as a result of following NDCs instead of least-cost action until 2030. A key finding is that carbon lock-ins persist long after 2030, with the majority of additional CO_2 emissions occurring during the 2030–2050 period. Luderer et al. (2018) find 90 (80–120) $GtCO_2$ additional emissions until 2030, growing to 240 (190–260) $GtCO_2$ by 2050 and 290 (200–200) $GtCO_2$ by 2100. As a result, peak warming is about 0.2°C higher and not all of the modelled pathways return warming to 1.5°C by the end of the century. There is a four sided trade-off between (i) near-term ambition, (ii) degree of overshoot, (iii) transitional challenges during the 2030–2050 period, and (iv) the amount of CDR deployment required during the century (Figure 2.13) (Holz et al., 2018b; Strefler et al., 2018b). Transition challenges, overshoot, and CDR requirements can be significantly reduced if global emissions peak before 2030 and fall below levels in line with current NDCs by 2030. For example, Strefler et al. (2018b) find that CDR deployment levels in the second half of the century can be halved in 1.5°C-consistent pathways with similar CO_2 emissions reductions rates during the 2030–2050 period if CO_2 emissions by 2030 are reduced by an additional 30% compared to NDC levels. Kriegler et al. (2018b) investigate a global roll out of selected regulatory policies and moderate carbon pricing policies. They show that additional reductions of ca. 10 $GtCO_2e\ yr^{-1}$ can be achieved in 2030 compared to the current NDCs. Such 20% reduction of year-2030 emissions compared to current NDCs would effectively lower the disruptiveness of post-2030 action. Strengthening of short-term policies in deep mitigation pathways has hence been identified as bridging options to keep the Paris climate goals within reach (Bertram et al., 2015b; IEA, 2015a; Spencer et al., 2015; Kriegler et al., 2018b).

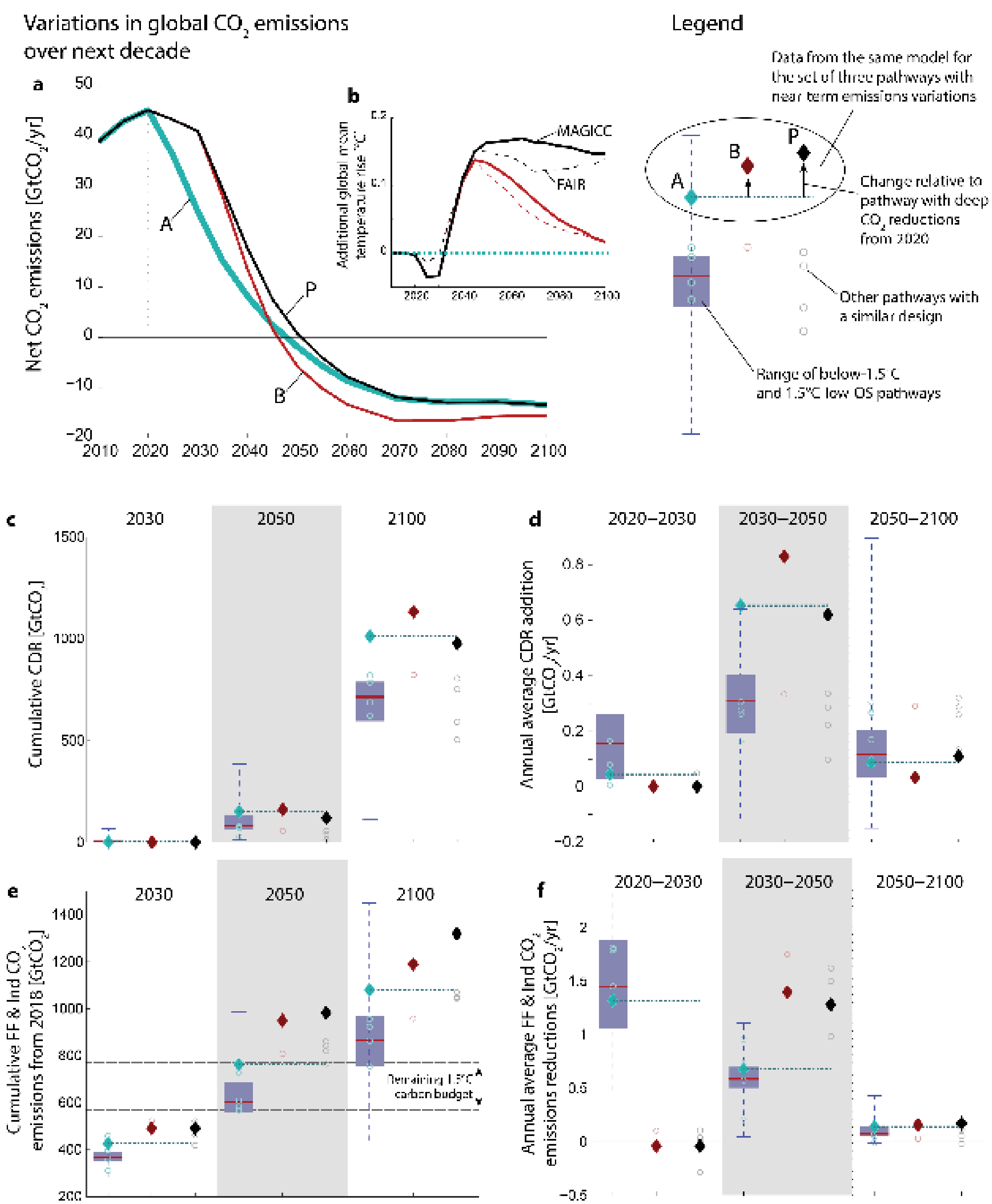

Figure 2.13: Comparison of pathways starting action for limiting warming to 1.5°C as of 2020 (A; light-blue diamonds) with pathways following the NDCs until 2030 and aiming to limit warming to 1.5°C thereafter. 1.5°C pathways following the NDCs either aim for the same cumulative CO_2 emissions by 2100 (B; red diamonds) or assume the same mitigation stringency as reflected by the price of emissions in associated least-cost 1.5°C-consistent pathways starting from 2020 (P; black diamonds)**.** Panels show the underlying emissions pathways (a), additional warming in the delay scenarios compared to 2020 action case (b), cumulated CDR (c), CDR ramp-up rates (d), cumulated gross CO_2 emissions from fossil-fuel combustion and industrial (FFI) processes over the 2018–2100 period (e), and gross FFI CO_2 emissions reductions rates (f). Scenario pairs / triplets (circles and diamonds) with 2020 and 2030 action variants were calculated by six (out of seven) models in the ADVANCE study symbols (Luderer et al., 2018) and five of them (passing near-term plausibility checks) are shown by symbols. Only two of five models could identify pathways with post-2030 action leading to a 2016–2100 carbon budget of ca. 200 $GtCO_2$ (red). The range of all 1.5°C-consistent pathways with no and low overshoot is shown by the boxplots.

2.4 Disentangling the whole-system transformation

Mitigation pathways map out prospective transformations of the energy, land and economic systems over this century (Clarke et al., 2014). There is a diversity of potential pathways consistent with 1.5°C, yet they share some key characteristics summarized in Table 2.5. To explore characteristics of 1.5°C pathways in greater detail, this section focuses on changes in energy supply and demand, and changes in the AFOLU sector.

Table 2.5: Overview of key characteristics of 1.5°C pathways.

1.5°C pathway characteristic	Supporting information	Reference
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass and reduction of unabated (no CCS) fossil fuels, along with the rapid deployment of CCS lead to a zero-emission energy supply system by mid-century.	Section 2.4.1 Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show marked demand reductions beyond the reductions projected for 2°C pathways. Demand reductions from IAMs for 2030 and 2050 lie within the potential assessed by detailed sectorial bottom-up assessments.	Section 2.4.3
Switching from fossil fuels to electricity in end-use sectors	Both in the transport and the residential sector, electricity covers marked larger shares of total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Virtually all 1.5°C-consistent pathways decline net annual CO_2 emissions between 2020 and 2030, reaching carbon neutrality around mid-century. Below-1.5°C and 1.5°C-low-OS show maximum net CO2 emissions in 2030 of 18 and 28 $GtCO_2\ yr^{-1}$, respectively. GHG emissions in these scenarios are not higher than 34 $GtCO_2e\ yr^{-1}$ in 2030.	Section 2.3.4
Additional reductions, on top of reductions from both CO2 and non-CO2 required for 2°C, are mainly from CO2	Both CO_2 and the non-CO_2 GHGs and aerosols are strongly reduced by 2030 and until 2050 in 1.5°C pathways. The greatest difference to 2°C pathways, however, lies in additional reductions of CO_2, as the non-CO_2 mitigation potential that is currently included in integrated pathways is mostly already fully deployed for reaching a 2°C pathway.	Section 2.3.1.2
Considerable shifts in investment patterns	Low-carbon investments in the energy supply side (energy production and refineries) are projected to average 1.6-3.8 trillion 2010USD yr^{-1} globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most available 1.5°C-consistent projections, while the literature is less conclusive for investments in unabated gas and oil. Energy demand investments are a critical factor for which total estimates are uncertain.	Section 2.5.2
Options are available to align 1.5°C pathways with sustainable development	Synergies can be maximized, and risks of trade-offs limited or avoided through an informed choice of mitigation strategies. Particularly pathways that focus on a lowering of demand show many synergies and few trade-offs.	Section 2.5.3
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 3–7 $GtCO_2yr^{-1}$ (range of medians across 1.5°C pathway classes), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C pathways are available that do not use BECCS, but only focus terrestrial CDR in the AFOLU sector.	Section 2.3.3, 2.3.4.1

2.4.1 Energy System Transformation

The energy system links energy supply (Section 2.4.2) with energy demand (Section 2.4.3) through final energy carriers including electricity and liquid, solid or gaseous fuels that are tailored to their end-uses. To chart energy-system transformations in mitigation pathways, four macro-level decarbonisation indicators associated with final energy are useful: limits to the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon intensity of final energy other than electricity (referred to in this section as the carbon intensity of the residual fuel mix). Figure 2.14 shows changes of these four indicators for the pathways in the scenario database (Section 2.1.3 and Annex 2.A.3) for 1.5°C and 2°C pathways (Table 2.1).

Pathways in both the 1.5°C and 2°C classes (Figure 2.14) generally show rapid transitions until mid-century with a sustained but slower evolution thereafter. Both show an increasing share of electricity accompanied by a rapid decline in the carbon intensity of electricity. Both also show a generally slower decline in the carbon intensity of the residual fuel mix, which arises from the decarbonisation of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector.

The largest differences between 1.5°C and 2°C pathways are seen in the first half of the century (Figure 2.14), where 1.5°C pathways generally show lower energy demand, a faster electrification of energy end-use, and a faster decarbonisation of the carbon intensity of electricity and the residual fuel mix. There are very few pathways in the Below-1.5°C class (Figure 2.14). Those scenarios that are available, however, show a faster decline in the carbon intensity of electricity generation and residual fuel mix by 2030 than most pathways that are projected to temporarily overshoot 1.5°C and return by 2100 (or 2°C pathways), and also appear to distinguish themselves already by 2030 by reductions in final energy demand and an increased electricity share (Figure 2.14).

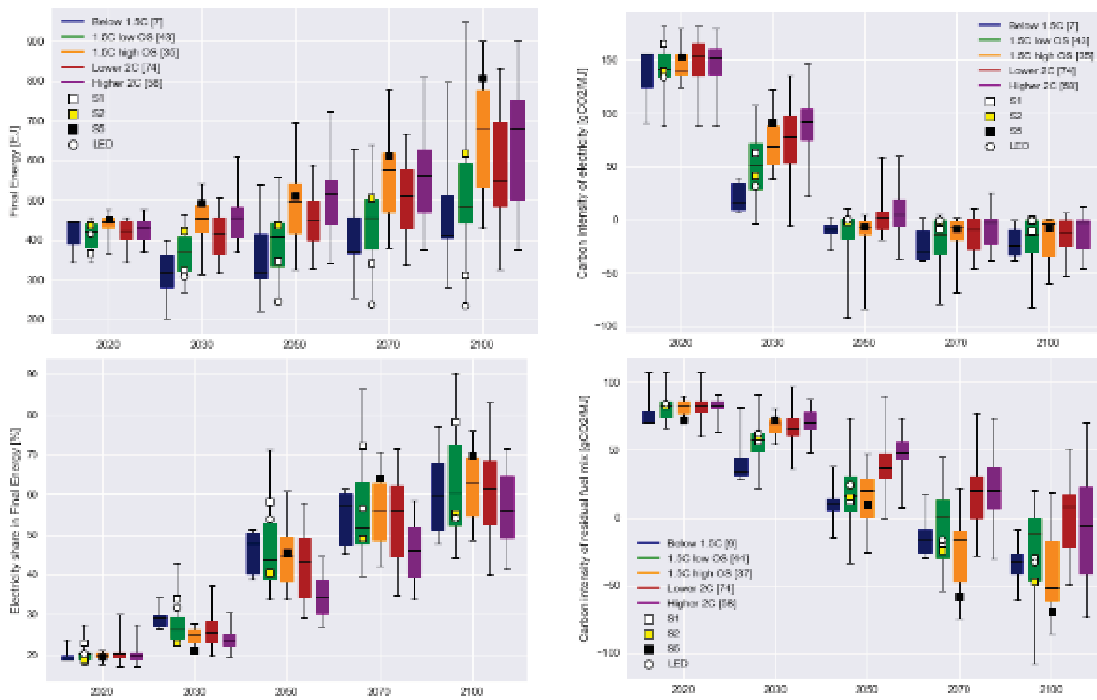

Figure 2.14: Decomposition of transformation pathways into energy demand (top left), carbon intensity of electricity (top right), the electricity share in final energy (bottom left), and the carbon intensity of the residual (non-electricity) fuel mix (bottom right). Boxplots show median, interquartile range and full range of pathways. Pathway temperature classes (Table 2.1) and illustrative pathway archetypes are indicated in the legend. Values following the class labels give the number of available pathways in each class.

2.4.2 Energy supply

Several energy supply characteristics are evident in 1.5°C pathways assessed in this section: i) growth in the share of energy derived from low carbon-emitting sources (including renewables, nuclear, and fossil fuel with CCS) and a decline in the overall share of fossil fuels without CCS (Section 2.4.2.1), ii) rapid decline in the carbon intensity of electricity generation simultaneous with further electrification of energy end-use (Section 2.4.2.2), and iii) the growth in the use of CCS applied to fossil and biomass carbon in most 1.5°C pathways (Section 2.4.2.3).

2.4.2.1 Evolution of primary energy contributions over time

By mid-century, the majority of primary energy comes from non-fossil-fuels (i.e., renewables and nuclear energy) in most 1.5°C pathways (Table 2.6). Figure 2.15 shows the evolution of primary energy supply over this century across 1.5°C pathways, and in detail for the four illustrative pathway archetypes highlighted in this chapter. Note that this section reports primary energy using the direct equivalent method on a lower heating values basis (Bruckner et al., 2014).

Renewable energy (including biomass, hydro, solar, wind, and geothermal) increases across all 1.5°C pathways with the renewable energy share of primary energy reaching 28–88% in 2050 (Table 2.6) with an interquartile range of 49–67%. The magnitude and split between bioenergy, wind, solar, and hydro differ between pathways, as can be seen in the illustrative pathway archetypes in Figure 2.15. Bioenergy is a major supplier of primary energy, contributing to both electricity and other forms of final energy such as liquid fuels for transportation (Bauer et al., 2018). In 1.5°C pathways, there is a significant growth in bioenergy used in combination with CCS for pathways where it is included (Figure 2.15).

Nuclear power increases its share in most 1.5°C pathways by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators declines (Table 2.15). There are large differences in nuclear power between models and across pathways (Kim et al., 2014; Rogelj et al., 2018). One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways (O'Neill et al., 2017; van Vuuren et al., 2017b). Some 1.5°C pathways no longer see a role for nuclear fission by the end of the century, while others project over 200 EJ yr^{-1} of nuclear power in 2100 (Figure 2.15).

The share of primary energy provided by total fossil fuels decreases from 2020 to 2050 in all 1.5°C pathways, however, trends for oil, gas and coal differ (Table 2.6). By 2050, the share of primary energy from coal decreases to 0–13% across 1.5°C pathways with an interquartile range of 1–7%. From 2020 to 2050 the primary energy supplied by oil changes by –93 to +6% (interquartile range –75 to –32%); natural gas changes by –88 to +99% (interquartile range –60 to –13%), with varying levels of CCS. Pathways with higher use of coal and gas tend to deploy CCS to control their carbon emissions (see Section 2.4.2.3). As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use (i.e., fossil fuels not used for electricity generation) without CCS is generally lower in 2050 than in 2°C pathways, while combined hydro, solar, and wind power deployment is generally higher than in 2°C pathways (Figure 2.15).

In addition to the 1.5°C pathways included in the scenario database (Annex 2.A.3), there are other analyses in the literature including, for example, sector-based analyses of energy demand and supply options. Even though not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transition to up to 100% renewable energy by 2050 (Creutzig et al., 2017; Jacobson et al., 2017), which describe what is entailed for a renewable energy share largely from solar and wind (and electrification) that is above the range of 1.5°C pathways available in the database, although there have been challenges to the assumptions used in high renewable analyses (e.g., Clack et al., 2017). There are also analyses that result in a large role for nuclear energy in mitigation of GHGs (Hong et al., 2015; Berger et al., 2017a, 2017b; Xiao and Jiang, 2017). BECCS could also contribute a larger share, but faces challenges related to its land use and impact on food supply (Burns and Nicholson, 2017) (assessed in greater detail in Sections 2.3.4.2, 4.3.7 and 5.4). These analyses could, provided their assumptions prove plausible, expand the range of 1.5°C pathways.

In summary, the share of primary energy from renewables increases while that from coal decreases across 1.5°C pathways (*high confidence*). This statement is true for all 1.5°C pathways in the scenario database and associated literature (Annex 2.A.3), and is consistent with the additional studies mentioned above, an increase in energy supply from lower-carbon-intensity energy supply, and a decrease in energy supply from higher-carbon-intensity energy supply.

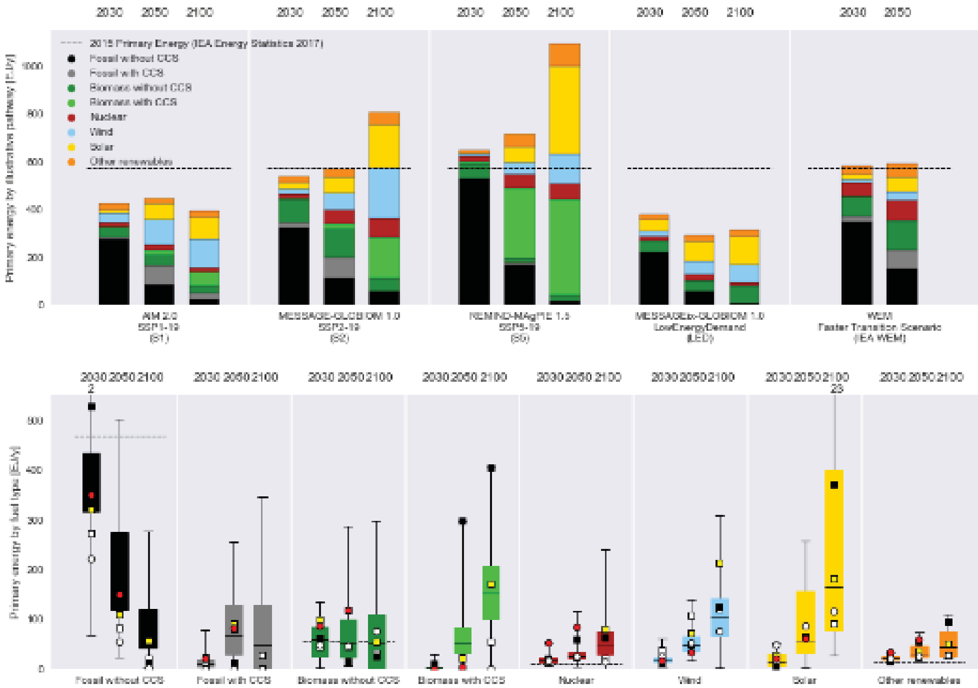

Figure 2.15: Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C pathway classes (lower panel). The category 'Other renewables' includes primary energy sources not covered by the other categories, for example, hydro and geothermal energy. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicates the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

Table 2.6: Global primary energy supply of 1.5°C pathways from the scenario database (Annex 2.A.3). Values given for the median (maximum, minimum) across the full range of 85 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Primary energy supply [EJ]			Share of primary energy [%]		Growth Factor
	2020	2030	2050	2020	2050	2020-2050
total primary	582.12 (636.98, 483.22)	502.81 (749.05, 237.37)	580.78 (1012.50, 289.02)			0.03 (0.59, -0.51)
renewables	87.70 (101.60, 60.16)	139.48 (203.90, 87.75)	293.80 (584.78, 176.77)	15.03 (20.39, 10.60)	60.80 (87.89, 28.47)	2.62 (6.71, 0.91)
biomass	61.35 (73.03, 40.54)	75.28 (113.02, 44.42)	154.13 (311.72, 40.36)	10.27 (14.23, 7.14)	26.38 (54.10, 10.29)	1.71 (5.56, -0.42)
non-biomass	26.35 (36.58, 17.60)	61.60 (114.41, 25.79)	157.37 (409.94, 53.79)	4.40 (7.19, 2.84)	28.60 (61.61, 9.87)	4.63 (13.46, 1.38)
nuclear	10.93 (18.55, 8.52)	16.22 (41.73, 6.80)	24.48 (115.80, 3.09)	1.97 (3.37, 1.45)	4.22 (13.60, 0.43)	1.34 (7.22, -0.64)
fossil	493.44 (638.04, 376.30)	347.62 (605.68, 70.14)	199.63 (608.39, 43.87)	83.56 (114.75, 77.73)	33.58 (74.63, 7.70)	-0.58 (0.12, -0.91)
coal	147.09 (193.55, 83.23)	49.46 (176.99, 5.97)	23.84 (134.69, 0.36)	25.72 (30.82, 17.19)	4.99 (13.30, 0.05)	-0.85 (-0.30, -1.00)
gas	135.58 (169.50, 105.01)	127.99 (208.55, 17.30)	88.97 (265.66, 14.92)	23.28 (28.39, 18.09)	13.46 (34.83, 2.80)	-0.37 (0.99, -0.88)
oil	195.02 (245.15, 151.02)	175.69 (319.80, 38.94)	93.48 (208.04, 15.07)	33.79 (42.24, 28.07)	16.22 (27.30, 2.89)	-0.54 (0.06, -0.93)

Table 2.7: Global electricity generation of 1.5°C pathways from the scenarios database (Annex 2.A.3). Values given for the median (maximum, minimum) values across the full range across 89 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Electricty generation [EJ]			Share of electricity generation [%]		Growth Factor
	2020	2030	2050	2020	2050	2020-2050
total electricity	100.09 (113.98, 83.53)	120.01 (177.51, 81.28)	224.78 (363.10, 126.96)			1.31 (2.55, 0.28)
renewables	26.38 (41.80, 18.26)	59.50 (111.70, 30.06)	153.72 (324.26, 84.69)	27.95 (41.84, 17.38)	77.52 (96.65, 35.58)	5.08 (10.88, 2.37)
biomass	1.52 (7.00, 0.66)	3.55 (11.96, 0.79)	16.32 (40.32, 0.21)	1.55 (7.30, 0.63)	8.02 (30.28, 0.08)	6.53 (38.14, -0.93)
non-biomass	24.48 (35.72, 17.60)	55.68 (101.90, 25.79)	136.40 (323.91, 53.79)	25.00 (40.43, 16.75)	66.75 (96.46, 27.51)	4.75 (10.64, 1.38)
nuclear	10.84 (18.55, 8.52)	15.49 (41.73, 6.80)	22.64 (115.80, 3.09)	10.91 (18.34, 8.62)	8.87 (39.61, 1.02)	1.21 (7.22, -0.64)
fossil	61.35 (76.76, 39.48)	38.41 (87.54, 2.25)	14.10 (118.12, 0.00)	61.55 (71.03, 47.26)	8.05 (33.19, 0.00)	-0.76 (0.54, -1.00)
coal	32.37 (46.20, 14.40)	10.41 (43.12, 0.00)	1.29 (46.72, 0.00)	32.39 (40.88, 17.23)	0.59 (12.87, 0.00)	-0.96 (0.01, -1.00)
gas	24.70 (41.20, 13.44)	25.00 (51.99, 2.01)	11.92 (67.94, 0.00)	24.71 (39.20, 11.80)	6.78 (32.59, 0.00)	-0.52 (1.63, -1.00)
oil	1.82 (13.36, 1.12)	0.92 (7.56, 0.24)	0.08 (8.78, 0.00)	2.04 (11.73, 1.01)	0.04 (3.80, 0.00)	-0.97 (0.98, -1.00)

2.4.2.2 *Evolution of electricity supply over time*

Electricity supplies an increasing share of final energy, reaching 34 to 71% in 2050, across 1.5°C pathways (Figure 2.14), extending the historical increases in electricity share seen over the past decades (Bruckner et al., 2014). From 2020 to 2050, the quantity of electricity supplied in most 1.5°C pathways more than doubles (Table 2.7). By 2050, the carbon intensity of electricity has fallen rapidly to -92 to +11 gCO_2/MJ electricity across 1.5°C pathways from a value of around 140 gCO_2/MJ (range: 88–181 gCO_2/MJ) in 2020 (Figure 2.14). A negative contribution to carbon intensity is provided by BECCS in most pathways (Figure 2.16).

By 2050, the share of electricity supplied by renewables increases from 23% in 2015 (IEA, 2017b) to 36–97% across 1.5°C pathways. Wind, solar, and biomass together make a major contribution in 2050, although the share for each spans a wide range across 1.5°C pathways (Figure 2.16). Fossil fuels on the other hand have a decreasing role in electricity supply with their share falling to 0–33% by 2050 (Table 2.7).

In summary, 1.5°C pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use (*high confidence*). This is the case across all 1.5°C pathways and their associated literature (Annex 2.A.3), with pathway trends that extend those seen in past decades, and results that are consistent with additional analyses (see Section 2.4.2.2).

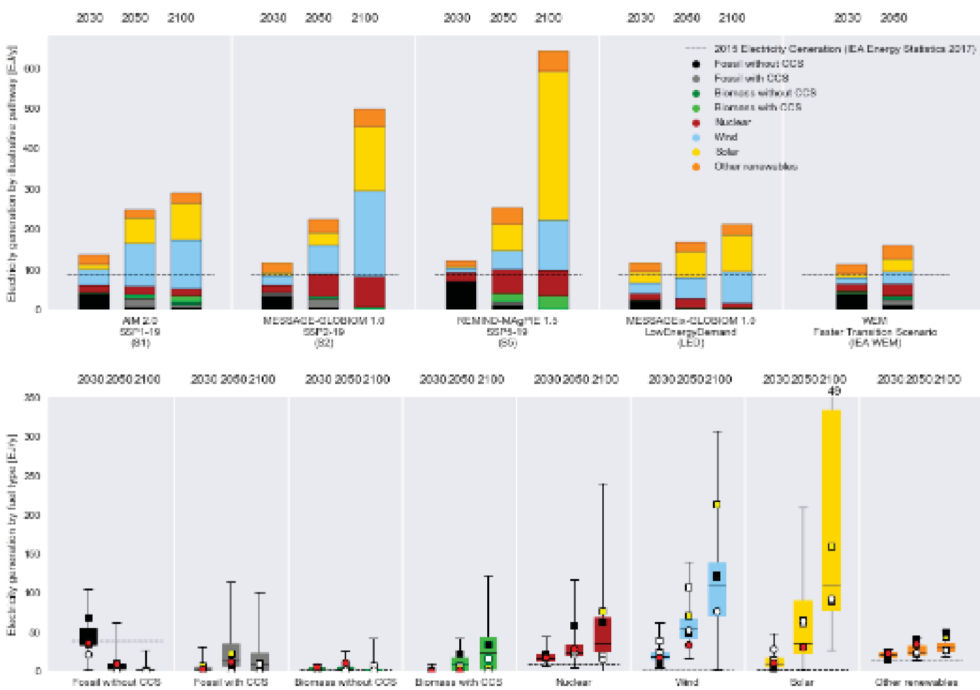

Figure 2.16: Electricity generation for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C scenario classes (lower panel). The category 'Other renewables' includes electricity generation not covered by the other categories, for example, hydro and geothermal. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

2.4.2.3 *Deployment of Carbon Capture and Storage*

Studies have shown the importance of CCS for deep mitigation pathways (Krey et al., 2014a; Kriegler et al., 2014b), based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO_2 from the atmosphere when combined with bioenergy. This remains a valid finding for those 1.5°C and 2°C pathways that do not radically reduce energy demand nor offer carbon-neutral alternatives to liquids and gases that do not rely on bioenergy.

There is a wide range of CCS that is deployed across 1.5°C pathways (Figure 2.17). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2018). For example, the LED pathway has no CCS, whereas other pathways like the S5 pathway rely on a large amount of BECCS to get to net-zero carbon emissions. The cumulative fossil and biomass CO_2 stored through 2050 ranges from zero to 460 $GtCO_2$ across 1.5°C pathways, with zero up to 190 $GtCO_2$ from biomass captured and stored. Some pathways have very low fossil-fuel use overall, and consequently little CCS applied to fossil fuels. In 1.5°C pathways where the 2050 coal use remains above 20 EJ yr^{-1} in 2050, 33–100% is combined with CCS. While deployment of CCS for natural gas and coal vary widely across pathways, there is greater natural gas primary energy connected to CCS than coal primary energy connected to CCS in many pathways (Figure 2.17).

CCS combined with fossil-fuel use remains limited in some 1.5°C pathways (Rogelj et al., 2018) as the limited 1.5°C carbon budget penalizes CCS if it is assumed to have incomplete capture rates or if fossil fuels are assumed to continue to have significant lifecycle GHG emissions (Pehl et al., 2017). However, high capture rates are technically achievable now at higher cost, although effort to date have focussed on cost reduction of capture (IEAGHG, 2006; DOE/NETL, 2013).

The quantity of CO_2 stored via CCS over this century in 1.5°C pathways ranges from zero to 1,900 $GtCO_2$, (Figure 2.17). The IPCC Special Report on on Carbon Dioxide Capture and Storage (IPCC, 2005) found that that, worldwide, it is *likely* that there is a technical potential of at least about 2,000 $GtCO_2$ of storage capacity in geological formations. Furthermore the IPCC (2005) recognised that there could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. Since IPCC (2005), understanding has improved and there have been detailed regional surveys of storage capacity (Vangkilde-Pedersen et al., 2009; Ogawa et al., 2011; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Warwick et al., 2014; NETL, 2015) and improvement and standardisation of methodologies (e.g., Bachu et al. 2007a, b). Dooley (2013) synthesised published literature on both the global geological storage resource as well as the potential demand for geologic storage in mitigation pathways, and found that the cumulative demand for CO_2 storage was small compared to a practical storage capacity estimate (as defined by Bachu et al., 2007a) of 3,900 $GtCO_2$ worldwide. Differences, however, remain in estimates of storage capacity due to, e.g. the potential storage limitations of subsurface pressure build-up (Szulczewski et al., 2014) and assumptions on practices that could manage such issues (Bachu, 2015). Kearns et al. (2017) constructed estimates of global storage capacity of 8,000 to 55,000 $GtCO_2$ (accounting for differences in detailed regional and local estimates), which is sufficient at a global level for this century, but found that at a regional level, robust demand for CO_2 storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates. In summary, the storage capacity of all of these global estimates is larger than the cumulative CO_2 stored via CCS of 1.5°C pathways over this century.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Bruckner et al., 2014; Clarke et al., 2014; Riahi et al., 2017). Given the importance of CCS in most mitigation pathways and its current slow pace of improvement, the large-scale deployment of CCS as an option depends on the further development of the technology in the near term. Chapter 4 discusses how progress on CCS might be accelerated.

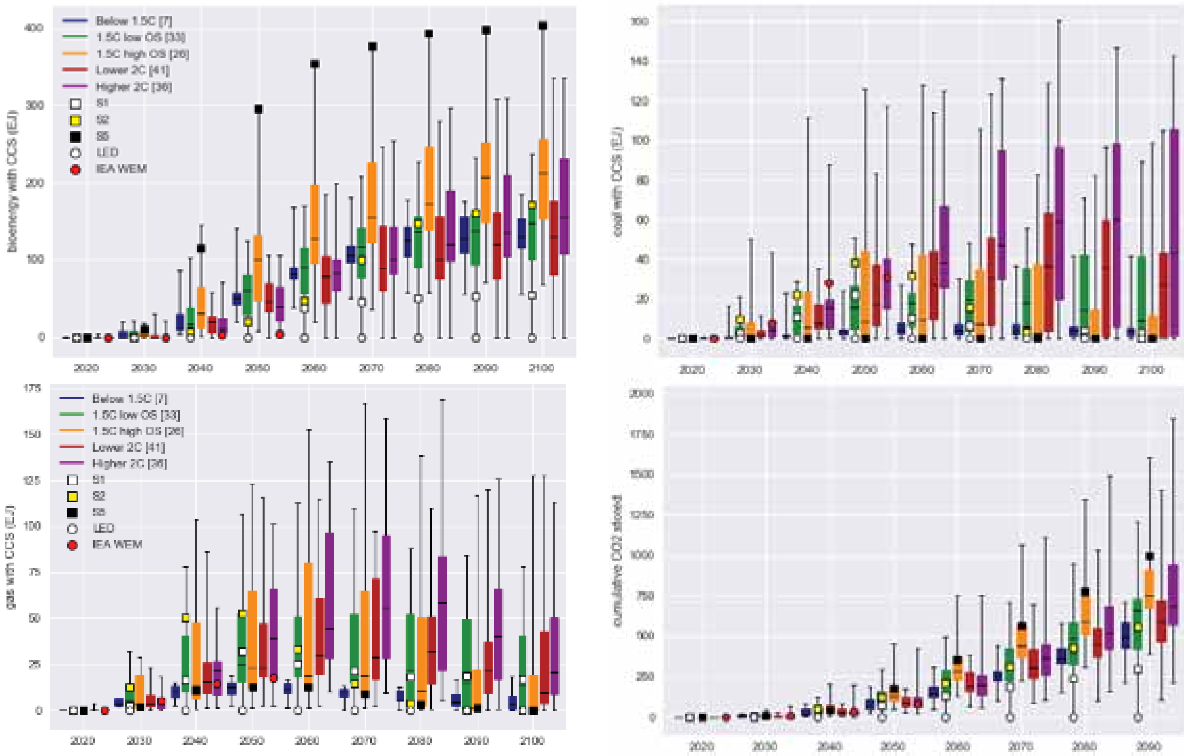

Figure 2.17: CCS deployment in 1.5°C and 2°C pathways for biomass, coal and natural gas (EJ of primary energy) and the cumulative quantity of fossil (including from, e.g., cement production) and biomass CO_2 stored via CCS (lower right in $GtCO_2$ stored). Boxplots show median, interquartile range and full range of pathways in each temperature class. Pathway temperature classes (Table 2.1), illustrative pathway archetypes, and the IEA's Faster Transition Scenario (IEA WEM) (OECD/IEA and IRENA, 2017) are indicated in the legend.

2.4.3 Energy end-use sectors

Since the power sector is almost decarbonized by mid-century in both 1.5°C and 2°C pathways, major differences come from CO_2 emission reductions in end-use sectors. Energy-demand reductions are key and common features in 1.5˚C-consistent pathways, which can be achieved by efficiency improvements and various specific demand-reduction measures. Another important feature is end-use decarbonisation including by electrification, although the potential and challenges in each end-use sector vary significantly.

In the following sections, the potential and challenges of CO_2 emission reductions towards 1.5°C and 2°C-consistent pathways are discussed for each end-use energy sector (industry, buildings, and transport sectors). For this purpose, two types of pathways are analysed and compared: IAM (integrated assessment modelling) studies and sectoral (detailed) studies. IAM data are extracted from the database that was compiled for this assessment (see Annex 2.A.3), and the sectoral data are taken from a recent series of publications; 'Energy Technology Perspectives' (ETP) (IEA, 2014, 2015b, 2016a, 2017a), the IEA/IRENA report (OECD/IEA and IRENA, 2017), and the Shell Sky report (Shell International B.V., 2018). The IAM pathways are categorized according to their temperature rise in 2100 and the overshoot of temperature during the century (see Table 2.1 in Section 2.1). Since the number of Below-1.5°C pathways is small, the following analyses focus only on the featured of the 1.5°C-low-OS and 1.5°C-high-OS pathways (hereafter denoted together as 1.5°C overshoot pathways or IAM-1.5DS-OS) and 2°C-consistent pathways (IAM-2DS). In order to show the diversity of IAM pathways, we again show specific data from the four illustrative pathways archetypes used throughout this chapter (see Sections 2.1 and 2.3).

IEA ETP-B2DS ('Beyond 2 Degrees') and ETP-2DS are pathways with a 50% chance of limiting temperature rise below 1.75°C and 2°C by 2100, respectively (IEA, 2017a). The IEA-66%2DS pathway keeps global-mean temperature rise below 2°C not just in 2100 but also over the course of the 21st century with a 66% chance of being below 2°C by 2100 (OECD/IEA and IRENA, 2017). The comparison of CO_2 emission trajectories between ETP-B2DS and IAM-1.5DS-OS show that these are consistent up to 2060 (Figure 2.18). IEA scenarios assume that only a very low level of BECCS is deployed to help offset emissions in difficult-to-decarbonize sectors, and that global energy-related CO_2 emissions cannot turn net-negative at any time and stay zero from 2060 to 2100 (IEA, 2017a). Therefore, although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to 1.5°C-consistent overshoot pathway up to 2050. The trajectory of IEA-66%2DS (also referred to in other publications as IEA's 'Faster Transition Scenario') lies between IAM-1.5DS-OS and IAM-2DS pathway ranges, and IEA-2DS stays in the range of 2°C-consistent IAM pathways. The Shell-Sky scenario aims to hold the temperature rise to well-below 2°C, but it is a delayed action pathway relative to others, as can be seen in Figure 2.18.

Energy-demand reduction measures are key to reduce CO_2 emissions from end-use sectors for low-carbon pathways. The up-stream energy reductions can be several times to an order of magnitude larger than the initial end-use demand reduction. There are interdependencies among the end-use sectors and also between energy-supply and end-use sectors, which raise the importance of a wide, systematic approach. As shown in Figure 2.19, global final-energy consumption grows by 30% and 10% from 2010 to 2050 for 2°C-consistent and 1.5°C overshoot pathways from IAMs, respectively, while much higher growth of 75% is projected for reference scenarios. The ranges within a specific pathway class are due to a variety of factors as introduced in Section 2.3.1, as well as differences between modelling frameworks. The important energy efficiency improvements and energy conservation that facilitate many of the 1.5°C pathways raise the issue of potential rebound effects (Saunders, 2015), which, while promoting development, can make the achievement of low-energy demand futures more difficult than modelling studies anticipate (see Sections 2.5 and 2.6).

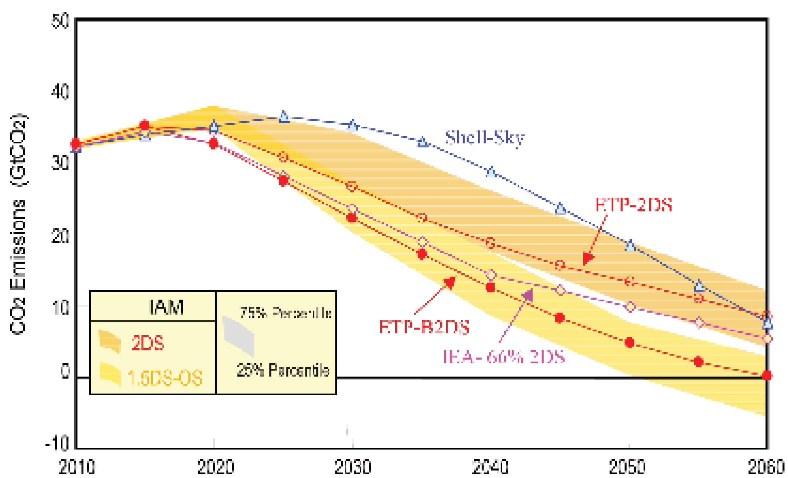

Figure 2.18: Comparison of CO_2 emission trajectories of sectoral pathways (IEA ETP-B2DS, ETP-2DS, IEA-66%2DS, Shell-Sky) with the ranges of IAM pathway (2DS are 2°C-consistent pathways and 1.5DS-OS are1.5°C-consistent overshoot pathways). The CO_2 emissions shown here are the energy-related emissions including industrial process emissions.

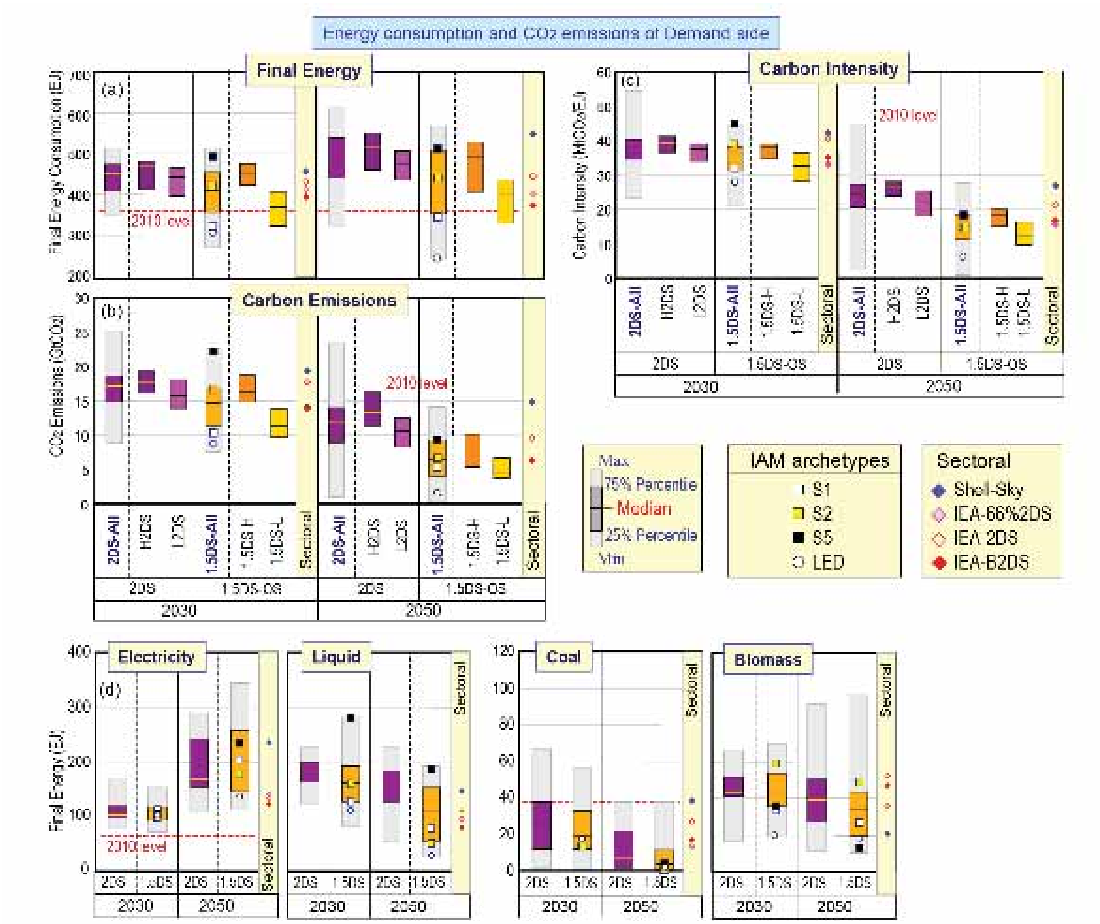

Figure 2.19: (a) Global final energy, (b) direct CO_2 emissions from the all energy demand sectors, (c) carbon intensity, and (d) structure of final energy (electricity, liquid fuel, coal, and biomass). The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Final-energy demand is driven by demand in energy services for mobility, residential and commercial activities (buildings), and manufacturing. This heavily depends on assumptions about socio-economic futures as represented by the SSPs (Bauer et al., 2017) (see Sections 2.1, 2.3 and 2.5). The structure of this demand drives the composition of final energy use in terms of energy carriers (electricity, liquids, gases, solids, hydrogen etc.).

Figure 2.19 shows the structure of global final energy demand in 2030 and 2050, indicating the trend toward electrification and fossil fuel usage reduction. This trend is more significant in 1.5°C pathways than 2°C pathways. Electrification continues throughout the second half of the century leading to a 3.5 to 6-fold increase in electricity demand (interquartile range; median 4.5) by the end of the century relative to today (Grubler et al., 2018; Luderer et al., 2018). Since the electricity sector is completely decarbonised by mid-century in 1.5°C pathways (see Figure 2.20), electrification is the primary means to decarbonize energy end-use sectors.

The CO_2 emissions[6] of end-use sectors and carbon intensity are shown in Figure 2.20. The projections of IAMs and IEA studies show rather different trends, especially in the carbon intensity. These differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency

[6] FOOTNOTE: This section reports “direct” CO_2 emissions as reported for pathways in the database for the report. As shown below, the emissions from electricity are nearly zero around 2050, so the impact of indirect emissions on the whole emission contributions of each sector is very small in 2050.

improvements, and the effect of structural and behavioural changes. IAM projections are generally optimistic for the industry sectors, but not for buildings and transport sectors. Although GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5°C overshoot and 2°C-consistent pathways, respectively. However, CO_2 emissions would need to be reduced further to achieve the stringent temperature limits. Fig. 2.20 shows that the reduction in CO_2 emissions of end-use sectors is larger and more rapid in 1.5°C overshoot than 2°C-consistent pathways, while emissions from the power sector are already almost zero in 2050 in both sets of pathways indicating that supply-side emissions reductions are almost fully exploited already in 2°C-consistent pathways (see Figure 2.20) (Rogelj et al., 2015b, 2018; Luderer et al., 2016b). The emission reductions in end-use sectors is largely made possible due to efficiency improvements, demand reduction measures and electrification, but its level differs among end-use sectors. While the carbon intensity of industry and the buildings sector decreases to a very low level of around 10 $gCO_2\ MJ^{-1}$, the carbon intensity of transport becomes the highest of any sector by 2040 due to its higher reliance on oil-based fuels. In the following subsections, the potential and challenges of CO_2 emission reduction in each end-use sector are discussed in detail.

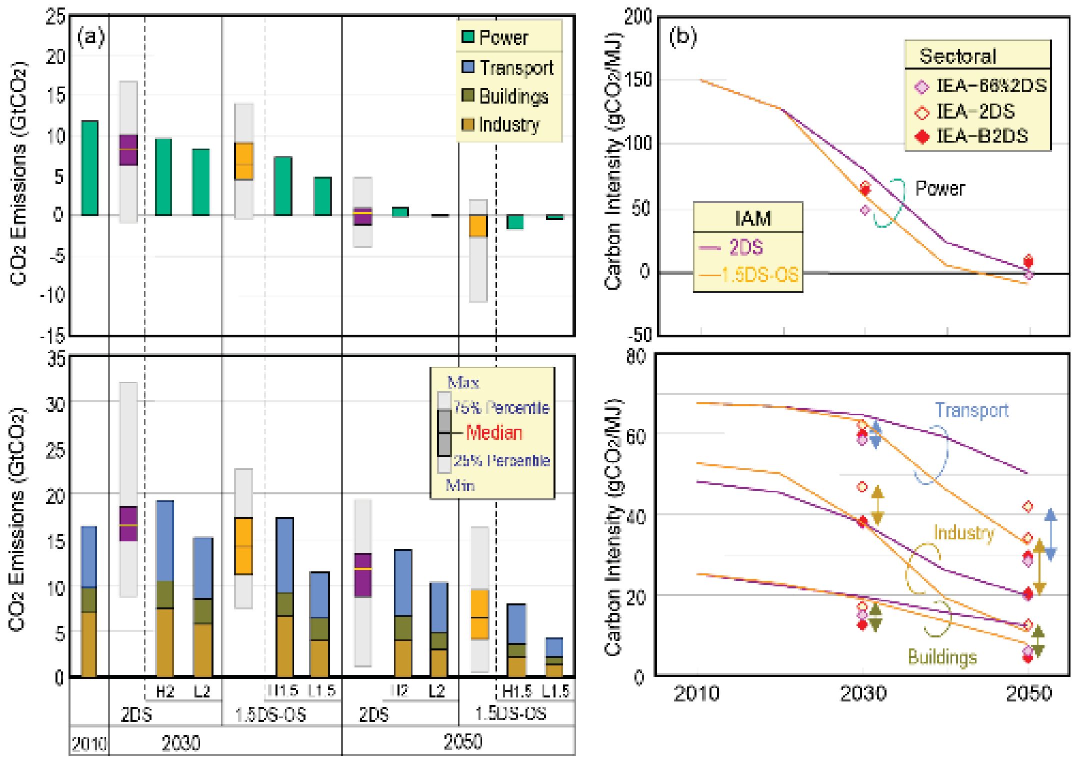

Figure 2.20: Comparison of (a) direct CO_2 emissions and (b) carbon intensity of the power and energy end-use sectors (industry, buildings, and transport sectors) between IAMs and sectoral studies (IEA-ETP and IEA/IRENA). Diamond markers in panel (b) show data for IEA-ETP scenarios (2DS and B2DS), and IEA/IRENA scenario (66%2DS). Note: for the data of IAM studies, there is rather large variation of projections for each indicator. Please see the details in the following figures in each end-use sector section.

2.4.3.1 Industry

The industry sector is the largest end-use sector both in terms of final-energy demand and GHG emissions. Its direct CO_2 emissions currently account for about 25% of total energy-related and process CO_2 emissions, and have increased with an average annual rate of 3.4% between 2000 and 2014, significantly faster than total CO_2 emissions (Hoesly et al., 2018). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossil fuels in the petro-chemical industry and metal smelting, as well as non-fossil fuel process emissions (e.g., from cement production) contribute a small amount (~5%) to the sector's CO_2 emissions inventory. Material industries are particularly energy and emissions intensive: steel, non-ferrous metals, chemicals, non-metallic minerals, and pulp and paper alone accounted for close to 66% of final-energy demand, and 72% of direct industry sector emissions in 2014 (IEA, 2017a). In terms of end-uses, the bulk of energy in manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) is used for mechanical work (Banerjee et al., 2012; IEA, 2017a).

As shown in Figure 2.21, a major share of the additional emission reductions required for 1.5°C-overshoot pathways beyond those in 2°C-consistent pathways comes from industry. Final energy, CO_2 emissions, and carbon intensity are consistent in IAM and sectoral studies, but in IAM-1.5°C-overshoot pathways the share of electricity is higher than IEA-B2DS (40% vs. 25%) and hydrogen is also considered to have a share of about 5% vs. 0%. In 2050, final energy is increased by 30% and 5% compared with the 2010 level (red dotted line) for 1.5°C-overshoot and 2°C-consistent pathways, respectively, but CO_2 emissions are decreased by 80% and 50% and carbon intensity by 80% and 60%, respectively. This additional decarbonisation is brought by switching to low carbon fuels and CCS deployment.

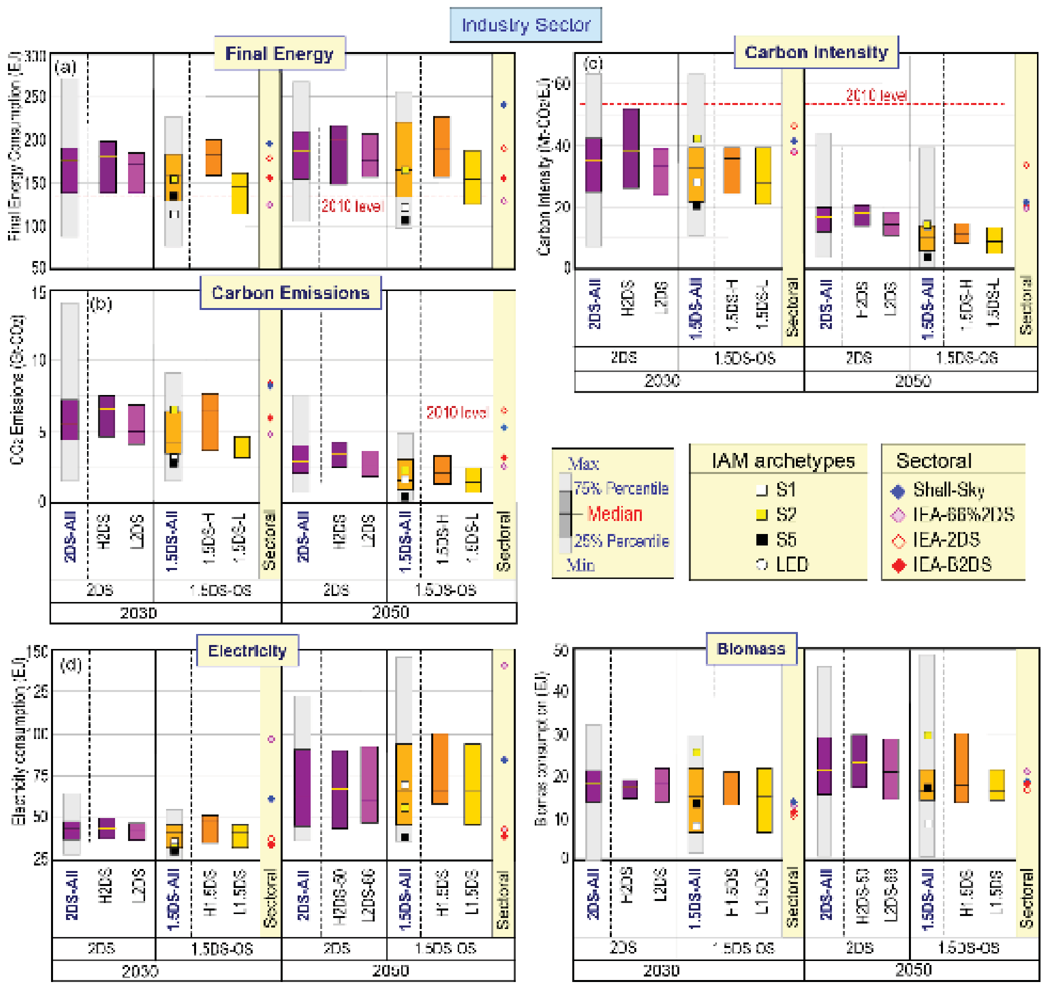

Figure 2.21: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the industry sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reductions in the demand, (ii) energy efficiency, (iii) increased electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of CCS. IEA ETP estimates the relative contribution of different measures for CO_2 emission reduction in their B2DS scenario compared with their reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low carbon fuels and feed-stocks 13% and material efficiency (include efficient production and use to contribute to demand reduction) 8%. The remainder of this section delves more deeply into the potential mitigation contributions of these strategies as well as their limitations.

Reduction in the use of industrial materials, while delivering similar services, or improving the quality of products could help to reduce energy demand and overall system-level CO_2 emissions. Strategies include using materials more intensively, extension of product lifetimes, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; IEA, 2017a). Related to material efficiency, use of fossil-fuel feed-stocks could shift to lower-carbon feed-stocks such as oil to natural gas and biomass and end-uses could shift to more sustainable materials such as biomass-based materials, reducing the demand for energy-intensive materials (IEA, 2017a).

Reaping energy efficiency potentials hinges critically on advanced management practices in industrial facilities such as energy management systems, as well as targeted policies to accelerate adoption of best available technology (see Section 2.5). Although excess energy, usually as waste heat, is inevitable, recovering and reusing this waste heat under economically and technically viable conditions benefits the overall energy system. Furthermore, demand-side management strategies could modulate the level of industrial activity in line with the availability of resources in the power system. This could imply a shift away from peak demand and as power supply decarbonizes, this demand-shaping potential could shift some load to times with high portions of low-carbon electricity generation (IEA, 2017a).

In the industry sector, energy demand increases more than 40% between 2010 and 2050 in baseline scenarios. However, in the 1.5°C-overshoot and 2°C-consistent pathways from IAMs, the increase is only 30% and 5%, respectively (Figure 2.21). These energy demand reductions encompass both efficiency improvements in production as well as reductions in material demand, as most IAMs do not discern these two factors.

CO_2 emissions from industry increase by 30% in 2050 compared to 2010 in baseline scenarios. By contrast, these emissions are reduced by 80% and 50% relative to 2010 levels in 1.5°C-overshoot and 2°C-consistent pathways from IAMs, respectively (Figure 2.21). By mid-century, CO_2 emissions per unit electricity are projected to decrease to near zero in both sets of pathways (see Figure 2.20). An accelerated electrification of the industry sector thus becomes an increasingly powerful mitigation option. In the IAM pathways, the share of electricity increases up to 30% by 2050 in 1.5°C-overshoot pathways (Figure 2.21) from 20% in 2010. Some industrial fuel uses are substantially more difficult to electrify than others, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (IEA, 2017a)[7].

In 1.5°C-overshoot pathways, the carbon intensity of non-electric fuels consumed by industry decreases to 16 $gCO_2\ MJ^{-1}$ by 2050, compared to 25 $gCO_2\ MJ^{-1}$ in 2°C-consistent pathways. Considerable carbon intensity reductions are already achieved by 2030, largely via a rapid phase-out of coal. Biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonisation pathways, but primarily in the longer term (in 2050, biomass accounts for only 10% of final energy consumption even in 1.5°C-overshoot pathways). In addition, hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands in some pathways.

Without major deployment of new sustainability-oriented low-carbon industrial processes, the 1.5°C-overshoot target is difficult to achieve. Bringing such technologies and processes to commercial deployment requires significant investment in research and development. Some examples of innovative low-carbon process routes include: new steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron, inert anodes for aluminium smelting, and full oxy-fuelling kilns for clinker production in cement manufacturing (IEA, 2017a).

[7] FOOTNOTE: Electrification can be linked with the heating and drying process by electric boilers and electro-thermal processes, and also low-temperature heat demand by heat pumps. In iron and steel industry, hydrogen produced by electrolysis can be used as a reduction agent of iron instead of coke. Excess resources, such as black liquor will provide the opportunity to increase the systematic efficiency to use for electricity generation.

CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement, iron and steel industries. In 1.5°C-overshoot pathways, CCS in industry reaches 3 $GtCO_2\ yr^{-1}$ by 2050, albeit with strong variations across pathways. Given project long-lead times and the need for technological innovation, early scale-up of industry CCS is essential to achieve the stringent temperature target. Development and demonstration of such projects has been slow, however. Currently, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The estimated current cost[8] of CO_2 avoided (in 2015-US$) ranges from $20-27 tCO_2^{-1} for gas processing and bio-ethanol production, and $60-138 tCO_2^{-1} for fossil fuel-fired power generation up to $104-188 tCO_2^{-1} for cement production (Irlam, 2017).

2.4.3.2 *Buildings*

In 2014, the buildings sector accounted for 31% of total global final-energy use, 54% of final-electricity demand, and 8% of energy-related CO_2 emissions (excluding indirect emission due to electricity). When upstream electricity generation is taken into account, buildings were responsible for 23% of global energy-related CO_2 emissions, with one-third of those from direct fossil fuel consumption (IEA, 2017a).

Past growth of energy consumption has been mainly driven by population and economic growth, with improved access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards, especially in developing countries (Lucon et al., 2014). These trends will continue in the future and in 2050, energy consumption is projected to increase by 20% (50%) compared to 2010 in IAM-1.5°C-overshoot (2°C-consistent) pathways (Figure 2.22). However, sectoral studies (IEA-ETP scenarios) show different trends. Energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO_2 emissions is higher than in IAM pathways (Figure 2.22). Mitigation options are often more widely covered in sectoral studies (Lucon et al., 2014), leading to greater reductions in energy consumption and CO_2 emissions.

Emissions reductions are driven by a clear tempering of energy demand and a strong electrification of the buildings sector. The share of electricity in 2050 is 60% in 1.5°C-overshoot pathways, compared with 50% in 2°C-consistent pathways (Figure 2.22). Electrification contributes to the reduction of direct CO_2 emissions by replacing carbon-intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonisation of the power system (see Section 2.4.1) it also enables further reduction of indirect CO_2 emissions from electricity. Sectoral bottom-up models in general estimate lower electrification potentials for the buildings sector in comparison to global IAMs (see Figure 2.22). Besides CO_2 emissions, increasing global demand for air conditioning in buildings may also lead to increased emissions of HFCs in this sector over the next few decades. Although these gases are currently a relatively small proportion of annual GHG emissions, their use in the air conditioning sector is expected to grow rapidly over the next few decades if alternatives are not adopted. However, their projected future impact can be significantly mitigated through better servicing and maintenance of equipment and switching of cooling gases (Shah et al., 2015; Purohit and Höglund-Isaksson, 2017).

IEA-ETP (IEA, 2017a) analysed the relative importance of various technology measures toward the reduction of energy and CO_2 emissions in the buildings sector. The largest energy savings potential is in heating and cooling demand largely due to building envelope improvements and high efficiency and renewable equipment. In the ETP-B2DS, energy demand for space heating and cooling is 33% lower in 2050 than the reference scenario and these reductions account for 54% of total reductions from the reference scenario. Energy savings from shifts to high-performance lighting, appliances, and water heating equipment account for a further 24% of the total reduction. The long-term, strategic shift away from fossil-fuel use in buildings, alongside the rapid uptake of energy efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction of CO_2 emissions. In ETP-B2DS, the direct CO_2 emissions are 79% lower than the reference scenario in 2050 and the remaining emissions come mainly from the continued use of natural gas.

[8] FOOTNOTE: These are first-of-a-kind (FOAK) cost data.

The buildings sector is characterized by very long-living infrastructure and immediate steps are hence important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to new buildings in developing countries where substantial new construction is expected in the near future and to retrofits of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation[9]. A recent study highlights the benefits of deploying the most advanced renovation technologies, which would avoid lock-in into less efficient measures (Güneralp et al., 2017). Aside from the effect of building envelope measures, adoption of energy-efficient technologies such as heat pumps and more recently light-emitting diodes is also important for the reduction of energy and CO_2 emissions (IEA, 2017a). Consumer choices, behaviour and building operation can also significantly affect energy consumption (see Section 4.3).

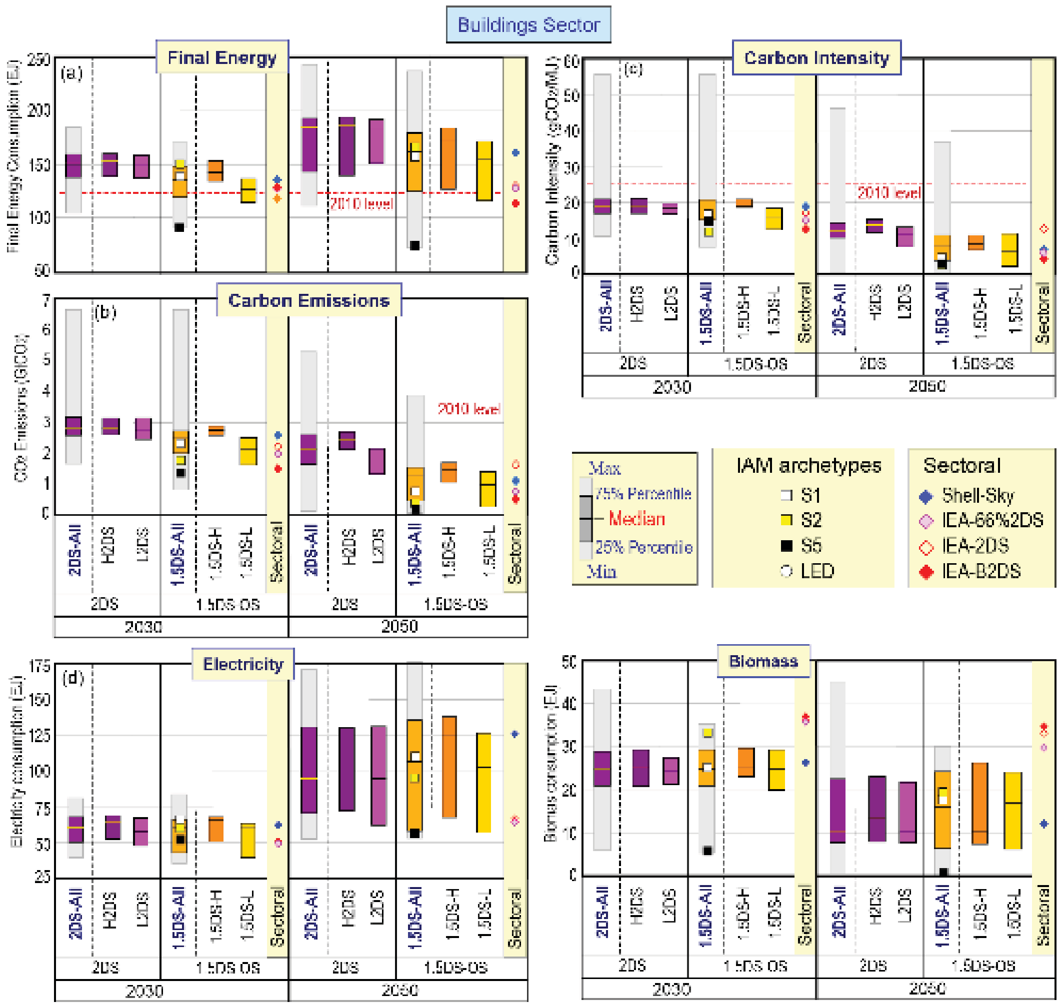

Figure 2.22: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the buildings sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

[9] FOOTNOTE: In this section, we only discuss the direct emissions from the sector, but the selection of building materials have a significant impact on the reduction of energy and emissions during the production, such as shift from the steel and concrete to wood-based materials.

2.4.3.3 *Transport*

Transport accounted for 28% of global final-energy demand and 23% of global energy-related CO_2 emissions in 2014. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other. The transport sector is the least diversified energy end-use sector; the sector consumed 65% of global oil final-energy demand, with 92% of transport final-energy demand consisting of oil products (IEA, 2017a), suggesting major challenges for deep decarbonisation.

Final energy, CO_2 emissions, and carbon intensity for the transport sector are shown in Figure 2.23. The projections of IAMs are more pessimistic than IEA-ETP scenarios, though both clearly project deep cuts in energy consumption and CO_2 emissions by 2050. For example, 1.5°C-overshoot pathways from IAMs project a reduction of 15% in energy consumption between 2015 and 2050, while ETP-B2DS projects a reduction of 30% (Figure 2.23). Furthermore, IAM pathways are generally more pessimistic in the projections of CO_2 emissions and carbon intensity reductions. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAMs and sectoral studies were performed and these were in good agreement with each other. Since the AR5, two important changes can be identified; rapid growth of electric vehicle sales in passenger cars, and more attention towards structural changes in this sector. The former contributes to reduction of CO_2 emissions and the latter reduction of energy consumption.

Deep emissions reductions in the transport sector would be achieved by several means. Technology focused measures such as energy efficiency and fuel-switching are two of these. Structural changes that avoid or shift transport activity are also important. While the former solutions (technologies) always tend to figure into deep decarbonisation pathways in a major way, this is not always the case with the latter, especially in IAM pathways. Comparing different types of global transport models, Yeh et al. (2016) find that sectoral (intensive) studies generally envision greater mitigation potential from structural changes in transport activity and modal choice. Though, even there, it is primarily the switching of passengers and freight from less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright reductions in travel demand (e.g., as a result of integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of structural changes in transport activity and modal choice is a point of investigation. According to the recent IEA-ETP scenarios, the share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO_2 emissions from the reference to B2DS scenarios in 2050 amounts to 20% (IEA, 2017a).

The potential and strategies to reduce energy consumption and CO_2 emissions differ significantly among transport modes. In ETP-B2DS, the shares of energy consumption and CO_2 emissions in 2050 for each mode are rather different (see Table 2.8), indicating the challenge of decarbonizing heavy-duty vehicles (HDV, trucks), aviation, and shipping. The reduction of CO_2 emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050, with varying contributions per mode (Table 2.8). Since there is no silver bullet for this deep decarbonisation, every possible measure would be required to achieve this stringent emissions outcome. The contribution of various measures for the CO_2 emission reduction from the reference scenario to the IEA-B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%) (IEA, 2017a). It is noted that the share of electrification becomes larger compared with older studies, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In IEA-B2DS, the total amount of biofuels consumed in the transport sector is 24EJ[10] in 2060, and allocated to LDV (light-duty vehicles, 17%), HDV (35%), aviation (28%), and shipping (21%), that is, more biofuels is allocated to the difficult-to-decarbonize modes (see Table 2.8).

[10] FOOTNOTE: This is estimated for the biofuels produced in a "sustainable manner" from non-food crop feed-stocks, which are capable of delivering significant lifecycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

Table 2.8: Transport sector indicators by mode in 2050 (IEA, 2017a). Share of Energy consumption, biofuel consumption, CO_2 emissions, and reduction of energy consumption and CO_2 emissions from 2014. (CO_2 emissions are Well-to-Wheel emissions, including the emission during the fuel production.), LDV: Light Duty Vehicle, HDV: Heavy Duty Vehicle

	Share of each mode (%)			Reduction from 2014 (%)	
	Energy	Biofuel	CO_2	Energy	CO_2
LDV	36	17	30	51	81
HDV	33	35	36	8	56
Rail	6		-1	-136	107
Aviation	12	28	14	14	56
Shipping	17	21	21	26	29

In road transport, incremental vehicle improvements (including engines) are relevant, especially in the short to medium term. Hybrid electric vehicles (HEVs) are also instrumental to enabling the transition from ICEs (internal combustion engine vehicles) to electric vehicles, especially plug-in hybrid electric vehicles (PHEVs). Electrification is a powerful measure to decarbonize short-distance vehicles (passenger cars and two and three wheelers) and the rail sector. In road freight transport (trucks), systemic improvements (e.g., in supply chains, logistics, and routing) would be effective measures with efficiency improvement of vehicles. Shipping and aviation are more challenging to decarbonize, while their demand growth is projected to be higher than other transport modes. Both modes would need to pursue highly ambitious efficiency improvements and use of low-carbon fuels. In the near and medium term, this would be advanced biofuels while in the long term it could be hydrogen as direct use for shipping or an intermediate product for synthetic fuels for both modes (IEA, 2017a).

The share of low-carbon fuels in the total transport fuel mix increases to 10% (16%) by 2030 and to 40% (58%) by 2050 in 1.5°C-overshoot pathways from IAMs. The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios, including the IAM pathways, regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.23, the projections of energy consumption, CO_2 emissions, and carbon intensity are quite different between IAM and ETP scenarios. These differences can be explained by more weight on efficiency improvements and avoid/shift decreasing energy consumption, and the higher share of biofuels and electricity accelerating the speed of decarbonisation in ETP scenarios. Although biofuel consumption and electric vehicle sales have increased significantly in recent years, the growth rates projected in these pathways would be unprecedented and far higher than has been experienced to date.

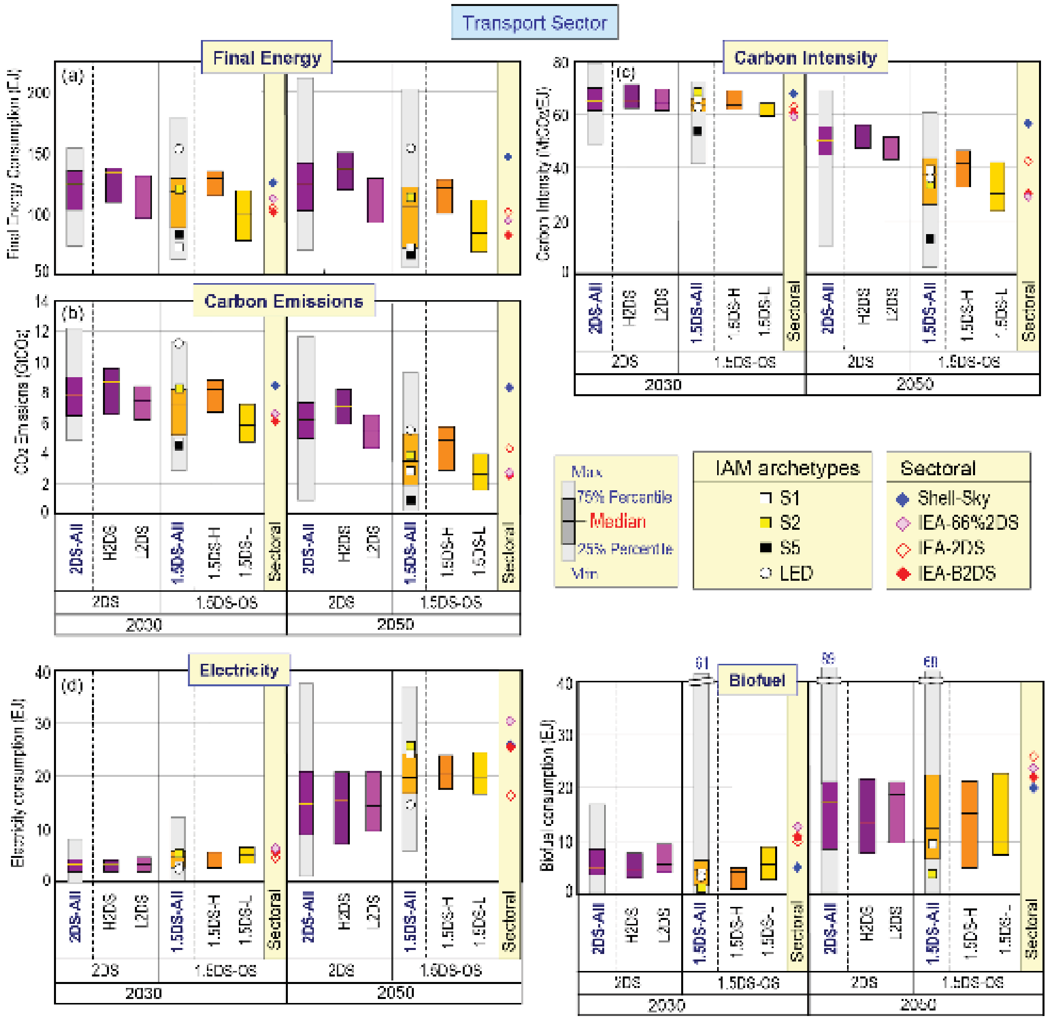

Figure 2.23: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biofuel consumption in the transport sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

1.5°C pathways require an acceleration of the mitigation solutions already featured in 2°C-consistent pathways (e.g., more efficient vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention in most global transport decarbonisation pathways up to now (e.g., mode-shifting and travel demand management). Current-generation, global pathways generally do not include these newer transport sector developments, whereby technological solutions are related to shifts in traveller's behaviour.

2.4.4 Land-use transitions and changes in the agricultural sector

The agricultural and land system described together under the umbrella of the AFOLU (Agriculture, Forestry, and Other Land Use) sector plays an important role in 1.5°C pathways (Clarke et al., 2014; Smith and Bustamante, 2014; Popp et al., 2017). On the one hand, its emissions need to be limited over the course of this century to be in line with pathways limiting warming to 1.5°C (see Sections 2.2-3). On the other hand, the AFOLU system is responsible for food and feed production, for wood production for pulp and construction, for the production of biomass that is used for energy, CDR or other uses, and for the supply of non-provisioning (ecosystem) services (Smith and Bustamante, 2014). Meeting all demands together requires changes in land use, as well as in agricultural and forestry practices, for which a multitude of potential options have been identified (Smith and Bustamante, 2014; Popp et al., 2017) (see also Annex 2.A.2 and Chapter 4, Section 4.3.1, 4.3.2 and 4.3.7).

This section assesses the transformation of the AFOLU system, mainly making use of pathways from IAMs (see Section 2.1) that are based on quantifications of the SSPs and that report distinct land-use evolutions in line with limiting warming to 1.5°C (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017b; Doelman et al., 2018; Rogelj et al., 2018). The SSPs were designed to vary mitigation challenges (O'Neill et al., 2014) (Cross-Chapter Box 1.1), including for the AFOLU sector (Popp et al., 2017; Riahi et al., 2017). The SSP pathway ensemble hence allows for a structured exploration of AFOLU transitions in the context of climate change mitigation in line with 1.5°C, taking into account technological and socio-economic aspects. Other considerations, like food security, livelihoods and biodiversity, are also of importance when identifying AFOLU strategies. These are at present only tangentially explored by the SSPs. Further assessments of AFOLU mitigation options are provided in other parts of this report and in the IPCC AR6 Special Report on Climate Change and Land (SRCCL). Chapter 4 provides an assessment of bioenergy (including feedstocks, see Section 4.3.1), livestock management (Section 4.3.1), reducing rates of deforestation and other land-based mitigation options (as mitigation and adaptation option, see Section 4.3.2), and BECCS, Afforestation and Reforestation options (including the bottom-up literature of their sustainable potential, mitigation cost and side effects, Section 4.3.7). Chapter 3 discusses impacts land-based CDR (Cross-Chapter Box 7 in Chapter 3). Chapter 5 assesses the sustainable development implications of AFOLU mitigation, including impacts on biodiversity (Section 5.4). Finally, the SRCCL will undertake a more comprehensive assessment of land and climate change aspects. For the sake of complementarity, this section focusses on the magnitude and pace of land transitions in 1.5°C pathways, as well as on the implications of different AFOLU mitigation strategies for different land types. The interactions with other societal objectives and potential limitations of identified AFOLU measures link to these large-scale evolutions, but these are assessed elsewhere (see above).

Land-use changes until mid-century occur in the large majority of SSP pathways, both under stringent and in absence of mitigation (Figure 2.24). In the latter case, changes are mainly due to socio-economic drivers like growing demands for food, feed and wood products. General transition trends can be identified for many land types in 1.5°C pathways, which differ from those in baseline scenarios and depend on the interplay with mitigation in other sectors (Figure 2.24) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Mitigation that demands land mainly occurs at the expense of agricultural land for food and feed production. Additionally, some biomass is projected to be grown on marginal land or supplied from residues and waste, but at lower shares. Land for second generation energy crops (such as miscanthus or poplar) expands by 2030 and 2050 in all available pathways that assume a cost-effective achievement of a 1.5°C temperature goal in 2100 (Figure 2.24), but the scale depends strongly on underlying socioeconomic assumptions (see later discussion of land pathway archetypes). Reducing rates of deforestation restricts agricultural expansion and forest cover can expand strongly in 1.5°C and 2°C pathways alike compared to its extent in no-climate policy baselines due to reduced deforestation, afforestation and reforestation measures. However, the extent to which forest cover expands varies highly across models in the literature, with some models projecting forest cover to stay virtually constant or decline slightly. This is due to whether afforestation and reforestation is included as a mitigation technology in these pathways and interactions with other sectors.

As a consequence of other land use changes, pasture land is generally projected to be reduced compared to both baselines in which no climate change mitigation action is undertaken and 2°C-consistent pathways. Furthermore, cropland for food and feed production decreases in most 1.5°C pathways, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by intensification on agricultural land and in livestock production systems (Popp et al., 2017), as well as changes in consumption patterns (Frank et al., 2017; Fujimori, 2017) (see also 4.3.2 for an assessment of these mitigation options). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017), global average cereal crop yields in 2100 are assumed to be above 5 tDM/ha.yr in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 W/m^2, compared to 4 tDM/ha.yr in the SSP5 baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. Historically, cereal crop yields are estimated at 1 tDM/ha.yr and ca. 3 tDM/ha.yr in 1965 and 2010, respectively (calculations based on FAOSTAT, 2017). For aggregate energy crops, models assume 4.2-8.9 tDM/ha.yr in 2010, increasing to about 6.9-17.4 tDM/ha.yr in 2050, which fall within the range found in the bottom-up literature yet depend on crop, climatic zone, land quality, and plot size (Searle and Malins, 2014).

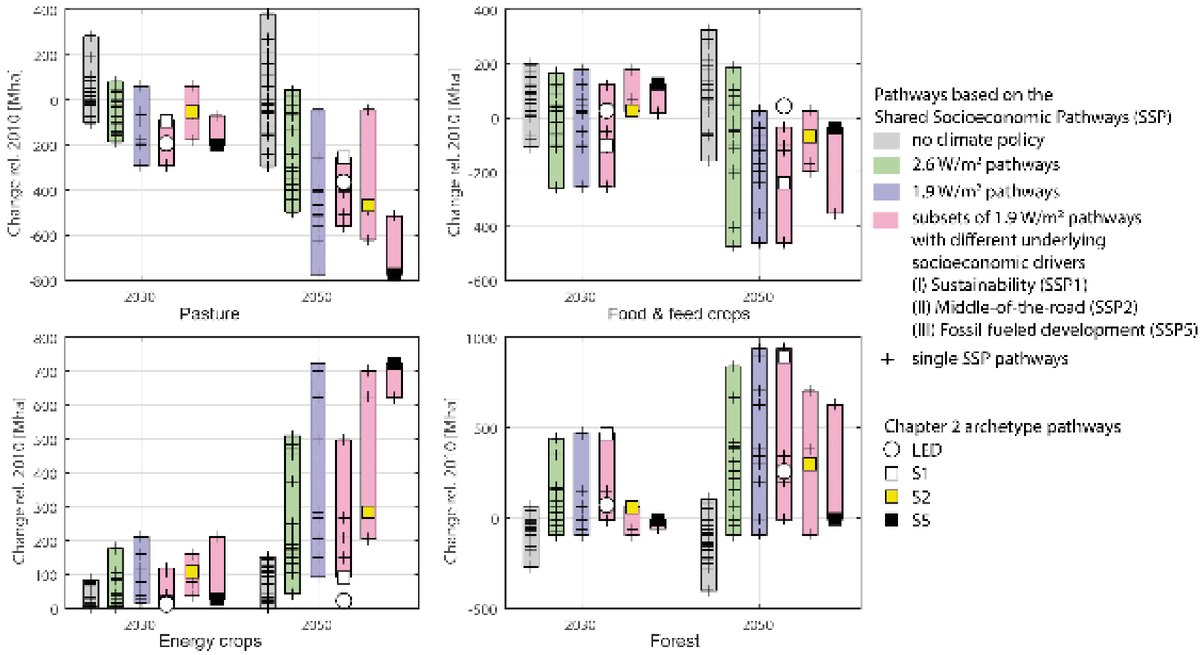

Figure 2.24: Overview of land-use change transitions in 2030 and 2050, relative to 2010 based on pathways based on the Shared Socioeconomic Pathways (SSP) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Grey: no-climate-policy baseline; green: 2.6 W/m^2 pathways; blue: 1.9 W/m^2 pathways. Pink: 1.9 W/m^2 pathways grouped per underlying socioeconomic assumption (from left to right: SSP1 sustainability, SSP2 middle-of-the-road, SSP5 fossil-fuelled development). Ranges show the minimum-maximum range across the SSPs. Single pathways are shown with plus signs. Illustrative archetype pathways are highlighted with distinct icons. Each panel shows the changes for a different land type. 1.9 and 2.6 W/m^2 are taken as proxies for 1.5°C and 2°C pathways, respectively. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. In 2010, pasture was estimated to cover about 3-3.5 10^3 Mha, food and feed crops about 1.5-1.6 10^3 Mha, energy crops about 0-14 Mha and forest about 3.7-4.2 10^3 Mha, across the models that reported SSP pathways (Popp et al., 2017).

The pace of projected land transitions over the coming decades can differ strongly between 1.5°C and baseline scenarios without climate change mitigation and from historical trends (Table 2.9). However, there is uncertainty in the sign and magnitude of these future land-use changes (Prestele et al., 2016; Popp et al., 2017; Doelman et al., 2018). The pace of projected cropland changes overlaps with historical trends over the past four decades, but in several cases also goes well beyond this range. By the 2030-2050 period, the projected reductions in pasture and potentially strong increases in forest cover imply a reversed dynamic compared to historical and baseline trends. For forest increases, this suggests that distinct policy and government measures would be needed to achieve this, particularly in a context of projected increased bioenergy use.

Table 2.9: Annual pace of land-use change in baseline, 2°C and 1.5°C pathways. All values in Mha/yr. 2.6 W/m² pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m² pathways are broadly consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. Baseline projections reflect land-use developments projected by integrated assessment models under the assumptions of the Shared Socioeconomic Pathways (SSP) in absence of climate policies (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Values give the full range across SSP scenarios. According to the Food and Agriculture Organization of the United Nations (FAOSTAT, 2017), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). FAO data in the table are equally from FAOSTAT (2017).

Annual pace of land-use change [Mha yr⁻¹] **Land type**	**Pathway**	**Time window**		**Historical**	
		2010-2030	**2030-2050**	**1970-1990**	**1990-2010**
Pasture	1.9 W m⁻²	[-14.6/3.0]	[-28.7/-5.2]	8.7	0.9
	2.6 W m⁻²	[-9.3/4.1]	[-21.6/0.4]	Permanent meadows and pastures (FAO)	Permanent meadows and pastures (FAO)
	Baseline	[-5.1/14.1]	[-9.6/9.0]		
Cropland for food, feed and material	1.9 W m⁻²	[-12.7/9.0]	[-18.5/0.1]		
	2.6 W m⁻²	[-12.9/8.3]	[-16.8/2.3]		
	Baseline	[-5.3/9.9]	[-2.7/6.7]		
Cropland for energy	1.9 W m⁻²	[0.7/10.5]	[3.9/34.8]		
	2.6 W m⁻²	[0.2/8.8]	[2.0/22.9]		
	Baseline	[0.2/4.2]	[-0.2/6.1]		
Total cropland	1.9 W m⁻²	[-6.8/12.8]	[-5.8/26.7]	4.6	0.9
(Sum of cropland for food and feed & energy)	2.6 W m⁻²	[-8.4/9.3]	[-7.1/17.8]	Arable land and Permanent crops	Arable land and Permanent crops
	Baseline	[-3.0/11.3]	[0.6/11.0]		
Forest	1.9 W m⁻²	[-4.8/23.7]	[0.0/34.3]	N.A.	-5.6
	2.6 W m⁻²	[-4.7/22.2]	[-2.4/31.7]	Forest (FAO)	Forest (FAO)
	Baseline	[-13.6/3.3]	[-6.5/4.3]		

Changes of the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Smith et al., 2013; Popp et al., 2017). Demand for agricultural products and other land-based commodities is influenced by consumption patterns (including dietary preferences and food waste affecting demand for food and feed) (Smith et al., 2013; van Vuuren et al., 2018), demand for forest products for pulp and construction (including less wood waste), and demand for biomass for energy production (Lambin and Meyfroidt, 2011; Smith and Bustamante, 2014). Efficiency of agricultural and forestry production relates to improvements in agricultural and forestry practices (including product cascades, by-products as well as more waste- and residue-based biomass for energy production), agricultural and forestry yield increases as well as intensification of livestock production systems leading to higher feed efficiency and changes in feed composition (Havlík et al., 2014; Weindl et al., 2015). Policy assumptions relate to the level of land protection, the treatment of food waste, policy choices about the timing of mitigation action (early vs late), the choice and preference of land-based mitigation options (for example, the inclusion of afforestation and reforestation as mitigation options), interactions with other sectors (Popp et al., 2017) and trade (Schmitz et al., 2012; Wiebe et al., 2015).

A global study (Stevanović et al., 2017) reported similar GHG reduction potentials for production (agricultural production measures in combination with reduced deforestation) and consumption side (diet change in combination with lower shares of food waste) measures of in the order of 40% in 2100[11] (compared to a baseline scenario without land-based mitigation). Lower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses (Weindl et al., 2017). On

[11] FOOTNOTE: Land-based mitigation options on the supply and the demand side are assessed in 4.3.2 and CDR options with a land component in 4.3.7. Chapter 5 (Section 5.4) assesses the implications of land-based mitigation for related SDGs, e.g., food security.

the supply side, minor productivity growth in extensive livestock production systems is projected to lead to substantial CO_2 emission abatement, but the emission saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks (Weindl et al., 2017). In addition, even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability (Gerber et al., 2013; Havlík et al., 2014). Many studies highlight the capability of agricultural intensification for reducing GHG emissions in the AFOLU sector or even enhancing terrestrial carbon stocks (Valin et al., 2013; Popp et al., 2014a; Wise et al., 2014). Also the importance of immediate and global land-use regulations for a comprehensive reduction of land-related GHG emissions (especially related to deforestation) has been shown by several studies (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017). Ultimately, there are also interactions between these three factors and the wider society and economy, for example, if CDR technologies that are not land based are deployed (like direct air capture – DACCS, see Chapter 4, Section 4.3.7) or if other sectors over- or underachieve their projected mitigation contributions (Clarke et al., 2014). Variations in these drivers can lead to drastically different land-use implications (Popp et al., 2014b) (Figure 2.24).

Stringent mitigation pathways inform general GHG dynamics in the AFOLU sector. First, CO_2 emissions from deforestation can be abated at relatively low carbon prices if displacement effects in other regions (Calvin et al., 2017) or other land-use types with high carbon density (Calvin et al., 2014; Popp et al., 2014a; Kriegler et al., 2017) can be avoided. However, efficiency and costs of reducing rates of deforestation strongly depend on governance performance, institutions and macroeconomic factors (Wang et al., 2016). Secondly, besides CO_2 reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2018) via BECCS, afforestation and reforestation, or a combination of options. The AFOLU sector also provides further potential for active terrestrial carbon sequestration, e.g., via land restoration, improved management of forest and agricultural land (Griscom et al., 2017), or biochar applications (Smith, 2016) (see also Section 4.3.7). These options have so far not been extensively integrated in the mitigation pathway literature (see Annex 2.A.2), but in theory their availability would impact the deployment of other CDR technologies, like BECCS (Section 2.3.4) (Strefler et al., 2018a). These interactions will be discussed further in the SRCCL.

Residual agricultural non-CO_2 emissions of CH_4 and N_2O play an important role for temperature stabilisation pathways and their relative importance increases in stringent mitigation pathways in which CO_2 is reduced to net zero emissions globally (Gernaat et al., 2015; Popp et al., 2017; Stevanović et al., 2017; Rogelj et al., 2018), for example, through their impact on the remaining carbon budget (Section 2.2). Although agricultural non-CO_2 emissions show marked reduction potentials in 2°C-consistent pathways, complete elimination of these emission sources does not occur in IAMs based on the evolution of agricultural practice assumed in integrated models (Figure 2.25) (Gernaat et al., 2015). CH_4 emissions in 1.5°C pathways are reduced through improved agricultural management (e.g., improved management of water in rice production, manure and herds, and better livestock quality through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products. Similarly, N_2O emissions decrease due to improved N-efficiency and manure management (Frank et al., 2018). However, high levels of bioenergy production can also result in increased N_2O emissions (Kriegler et al., 2017) highlighting the importance of appropriate management approaches (Davis et al., 2013). Residual agricultural emissions can be further reduced by limiting demand for GHG-intensive foods through shifts to healthier and more sustainable diets (Tilman and Clark, 2014; Erb et al., 2016b; Springmann et al., 2016) and reductions in food waste (Bajželj et al., 2014; Muller et al., 2017; Popp et al., 2017) (see also Chapter 4, and SRCCL). Finally, several mitigation measures that could affect these agricultural non-CO_2 emissions are not, or only to a limited degree, considered in the current integrated pathway literature (see Annex 2.A.2). Such measures (like plant-based and synthetic proteins, methane inhibitors and vaccines in livestock, alternate wetting and drying in paddy rice, or nitrification inhibitors) are very diverse and differ in their development or deployment stages. Their potentials have not been explicitly assessed here.

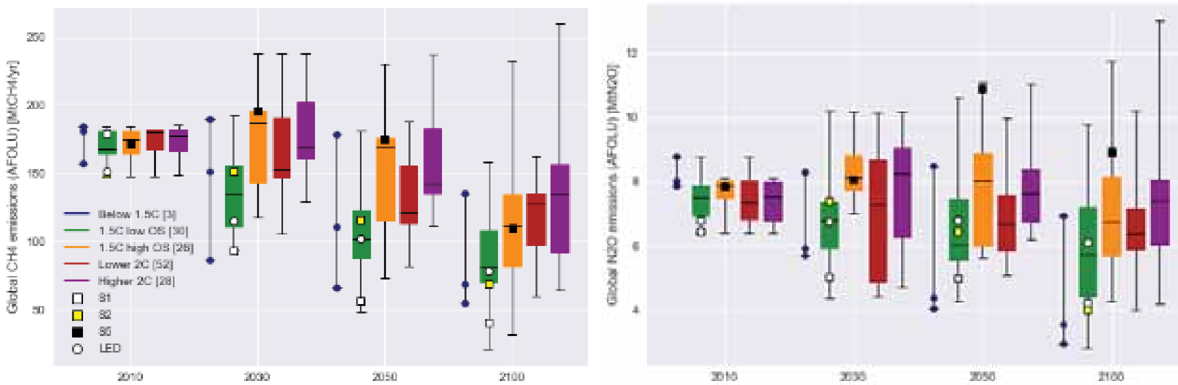

Figure 2.25: Agricultural emissions in transformation pathways. Global agricultural CH_4 (left) and N_2O (right) emissions. Boxplots show median, interquartile range and full range. Classes are defined in Section 2.1.

Pathways consistent with 1.5°C rely on one or more of the three strategies highlighted above (demand changes, efficiency gains, and policy assumptions), and can apply these in different configurations. For example, among the four illustrative archetypes used in this chapter (Section 2.1) the LED and S1 pathways focus on generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant agricultural intensification in combination with high levels of nature protection. Under such assumptions, comparably small amounts of land are needed for land demanding mitigation activities such as BECCS and afforestation and reforestation, leaving the land footprint for energy crops in 2050 virtually the same compared to 2010 levels for the LED pathway. In contrast, future land-use developments can look very differently under the resource- and energy-intensive S5 pathway that includes unhealthy diets with high animal shares and high shares of food waste (Tilman and Clark, 2014; Springmann et al., 2016) combined with a strong orientation towards technology solutions to compensate for high reliance on fossil-fuel resources and associated high levels of GHG emissions in the baseline. In such pathways, climate change mitigation strategies strongly depend on the availability of CDR through BECCS (Humpenöder et al., 2014). As a consequence, the S5 pathway sources significant amounts of biomass through bioenergy crop expansion in combination with agricultural intensification. Also, further policy assumptions can strongly affect land-use developments, highlighting the importance for land use of making appropriate policy choices. For example, within the SSP set, some pathways rely strongly on a policy to incentivise afforestation and reforestation for CDR together with BECCS, which results in an expansion of forest area and a corresponding increase in terrestrial carbon stock. Finally, the variety of pathways illustrates how policy choices in the AFOLU and other sectors strongly affect land-use developments and associated sustainable development interactions (Section 5.4) in 1.5°C pathways.

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system and other sectors (see Section 2.3), as well as the synergies and trade-offs with other environmental and societal objectives (see Section 2.5.3 and Section 5.4). For example, AFOLU developments in 1.5°C pathways range from strategies that differ almost an order of magnitude in their projected land requirements for bioenergy (Figure 2.24), and some strategies would allow an increase in forest cover over the 21st century compared to strategies under which forest cover remains approximately constant. High agricultural yields and application of intensified animal husbandry, implementation of best-available technologies for reducing non-CO_2 emissions, or lifestyle changes including a less-meat-intensive diet and less CO_2-intensive transport modes, have been identified to allow for such a forest expansion and reduced footprints from bioenergy without compromising food security (Frank et al., 2017; Doelman et al., 2018; van Vuuren et al., 2018).

The IAMs used in the pathways underlying this assessment (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) do not include all potential land-based mitigation options and side-effects, and their results are hence subject to uncertainty. For example, recent research has highlighted the potential impact of forest management practices on land carbon content (Erb et al., 2016a; Naudts et al., 2016) and the uncertainty surrounding future crop yields (Haberl et al., 2013; Searle and Malins, 2014), and water availability (Liu et al., 2014). These aspects are included in IAMs in varying degrees, but were not assessed in this report. Furthermore, land-use modules of some IAMs can depict spatially resolved climate damages to agriculture (Nelson et al., 2014), but this option was not used in the SSP quantifications (Riahi et al., 2017). Damages (e.g., due to ozone exposure or varying indirect fertilization due to atmospheric N and Fe deposition (e.g., Shindell et al., 2012; Mahowald et al., 2017) are also not included. Finally, this assessment did not look into the literature of agricultural sector models which could provide important additional detail and granularity to the here presented discussion[12]. This limits their ability to capture the full mitigation potentials and benefits between scenarios. An in-depth assessment of these aspects lies outside the scope of this Special Report. However, their existence affects the confidence assessment of the AFOLU transition in 1.5°C pathways.

Despite the limitations of current modelling approaches, there is *high agreement* and *robust evidence* across models and studies that the AFOLU sector plays an important role in stringent mitigation pathways. The findings from these multiple lines of evidence also result in *high confidence* that AFOLU mitigation strategies can vary significantly based on preferences and policy choices, facilitating the exploration of strategies that can achieve multiple societal objectives simultaneously (see also Section 2.5.3). At the same time, given the many uncertainties and limitations, only *low to medium confidence* can be attributed by this assessment to the more extreme AFOLU developments found in the pathway literature, and *low to medium confidence* to the level of residual non-CO_2 emissions.

[12] FOOTNOTE: For example, the GLEAM (http://www.fao.org/gleam/en/) model from the UN Food and Agricultural Organisation (FAO).

2.5 Challenges, opportunities and co-impacts of transformative mitigation pathways

This section examines aspects other than climate outcomes of 1.5°C mitigation pathways. Focus is given to challenges and opportunities related to policy regimes, price of carbon and co-impacts, including sustainable development issues, which can be derived from the existing integrated pathway literature. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways. The challenges and opportunities identified in this section are further elaborated Chapter 4 (e.g., policy choice and implementation) and Chapter 5 (e.g., sustainable development). The assessment indicates unprecedented policy and geopolitical challenges.

2.5.1 Policy frameworks and enabling conditions

Moving from a 2°C to a 1.5°C pathway implies bold integrated policies that enable higher socio-technical transition speeds, larger deployment scales, and the phase-out of existing systems that may lock in emissions for decades (Geels et al., 2017; Kuramochi et al., 2017; Rockström et al., 2017; Vogt-Schilb and Hallegatte, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018) (*high confidence*). This requires higher levels of transformative policy regimes in the near term, which allow deep decarbonisation pathways to emerge and a net zero carbon energy-economy system to emerge in the 2040–2060 period (Rogelj et al., 2015b; Bataille et al., 2016b). This enables accelerated levels of technological deployment and innovation (Geels et al., 2017; IEA, 2017a; Grubler et al., 2018) and assumes more profound behavioural, economic and political transformation (Sections 2.3, 2.4 and 4.4). Despite inherent levels of uncertainty attached to modelling studies (e.g., related to climate and carbon-cycle response), studies stress the urgency for transformative policy efforts to reduce emissions in the short term (Riahi et al., 2015; Kuramochi et al., 2017; Rogelj et al., 2018).

The available literature indicates that mitigation pathways in line with 1.5°C-consistent pathways would require stringent and integrated policy interventions (*very high confidence*). Higher policy ambition often takes the form of stringent economy-wide emission targets (and resulting peak-and-decline of emissions), larger coverage of NDCs to more gases and sectors (e.g., land-use, international aviation), much lower energy and carbon intensity rates than historically seen, carbon prices much higher than the ones observed in real markets, increased climate finance, global coordinated policy action, and implementation of additional initiatives (e.g., by non-state actors) (Sections 2.3, 2.4 and 2.5.2). The diversity (beyond carbon pricing) and effectiveness of policy portfolios are of prime importance, particularly in the short-term (Mundaca and Markandya, 2016; Kuramochi et al., 2017; OECD, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018). For instance, deep decarbonisation pathways in line with a 2˚C target (covering 74% of global energy-system emissions) include a mix of stringent regulation (e.g., building codes, minimum performance standards), carbon pricing mechanisms and R&D (research and development) innovation policies (Bataille et al., 2016a). Carbon pricing, direct regulation and public investment to enable innovation are critical for deep decarbonisation pathways (Grubb et al., 2014). Effective planning (including compact city measures) and integrated regulatory frameworks are also key drivers in the IEA-ETP B2DS study for the transport sector (IEA, 2017a). Effective urban planning can reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Comprehensive policy frameworks would be needed if the decarbonisation of the power system is pursued while increasing end-use electrification (including transport) (IEA, 2017a). Technology policies (e.g., feed-in-tariffs), financing instruments, carbon pricing and system integration management driving the rapid adoption of renewable energy technologies are critical for the decarbonisation of electricity generation (Bruckner et al., 2014; Luderer et al., 2014; Creutzig et al., 2017; Pietzcker et al., 2017). Likewise, low-carbon and resilient investments are facilitated by a mix of coherent policies including fiscal and structural reforms (e.g., labour markets), public procurement, carbon pricing, stringent standards, information schemes, technology policies, fossil-fuel subsidy removal, climate risk disclosure, and land-use and transport planning (OECD, 2017). Pathways in which CDR options are restricted emphasise the strengthening of near-term policy mixes (Luderer et al., 2013; Kriegler et al., 2018b). Together with the decarbonisation of the supply side, ambitious policies targeting fuel switching and energy efficiency improvements on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015; Kuramochi et al., 2017; Brown and Li, 2018; Rogelj et al., 2018; Wachsmuth and Duscha, 2018).

The combined evidence suggests that aggressive policies addressing energy efficiency are central in keeping 1.5°C within reach and lowering energy system and mitigation costs (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Grubler et al., 2018) (*high confidence*). Demand-side policies that increase energy efficiency or limit energy demand at a higher rate than historically observed are critical enabling factors reducing mitigation costs for stringent mitigation pathways across the board (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Clarke et al., 2014; Bertram et al., 2015a; Bataille et al., 2016b). Ambitious sector-specific mitigation policies in industry, transportation and residential sectors are needed in the short run for emissions to peak in 2030 (Méjean et al., 2018). Stringent demand-side policies (e.g., tightened efficiency standards for buildings and appliances) driving the expansion, efficiency and provision of high-quality energy services are essential to meet a 1.5˚C mitigation target while avoiding the need of CDR (Grubler et al., 2018). A 1.5˚C pathway for the transport sector is possible using a mix of additional and stringent policy actions preventing (or reducing) the need for transport, encouraging shifts towards efficient modes of transport, and improving vehicle-fuel efficiency (Ghota et al., 2018). Stringent demand-side policies also reduce the need for CCS (Wachsmuth and Duscha, 2018). Even in the presence of weak-near term policy frameworks, increased energy efficiency lowers mitigation costs noticeably compared to pathways with reference energy intensity (Bertram et al., 2015a). Horizontal issues in the literature relate to the rebound effect, the potential overestimation of the effectiveness of energy efficiency policy, and policies to counteract the rebound (Saunders, 2015; van den Bergh, 2017; Grubler et al., 2018) (Sections 2.4 and 4.4).

SSP-based modelling studies underline that socio-economic and climate policy assumptions strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (Bauer et al., 2017; Guivarch and Rogelj, 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). SSP assumptions related to economic growth and energy intensity are critical determinants of projected CO_2 emissions (Marangoni et al., 2017). A multi-model inter-comparison study found that mitigation challenges in line with a 1.5˚C target vary substantially across SSPs and policy assumptions (Rogelj et al., 2018). Under SSP1-SPA1 (sustainability) and SSP2-SPA2 (middle-of-the-road), the majority of IAMs were capable of producing 1.5˚C pathways. On the contrary, none of the IAMs contained in the SR1.5 database could produce a 1.5°C pathway under SSP3-SPA3 assumptions. Preventing elements include, for instance, climate policy fragmentation, limited control of land-use emissions, heavy reliance on fossil fuels, unsustainable consumption and marked inequalities (Rogelj et al., 2018). Dietary aspects of the SSPs are also critical: climate-friendly diets were contained in 'sustainability' (SSP1) and meat-intensive diets in SSP3 and SSP5 (Popp et al., 2017). CDR requirements are reduced under 'sustainability' related assumptions (Strefler et al., 2018b). These are major policy-related factors for why SSP1-SPA1 translates into relatively low mitigation challenges whereas SSP3-SPA3 and SSP5-SPA5 entail futures that pose the highest socio-technical and economic challenges. SSPs/SPAs assumptions indicate that policy-driven pathways that encompass accelerated change away from fossil fuels, large-scale deployment of low-carbon energy supplies, improved energy efficiency and sustainable consumption lifestyles reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015, 2017; Marangoni et al., 2017; Rogelj et al., 2017, 2018; Strefler et al., 2018b).

Policy assumptions that lead to weak or delayed mitigation action from what would be possible in a fully cooperative world, strongly influence the achievability of mitigation targets (Luderer et al., 2013; Rogelj et al., 2013; OECD, 2017; Holz et al., 2018a; Strefler et al., 2018b) (*high confidence*). Such regimes also include current NDCs (Fawcett et al., 2015; Aldy et al., 2016; Rogelj et al., 2016a, 2017; Hof et al., 2017; van Soest et al., 2017), which have been reported to make achieving a 2°C pathway unattainable without CDR (Strefler et al., 2018b). Not strengthening NDCs make it very challenging to keep 1.5°C within reach (see Section 2.3 and Cross-Chapter Box 11 in Chapter 4). One multi-model inter-comparison study (Luderer et al., 2016b, 2018) explored the effects on 1.5°C pathways assuming the implementation of current NDCs until 2030 and stringent reductions thereafter. It finds that delays in globally coordinated actions leads to various models reaching no 1.5°C-consistent pathways during the 21st century. Transnational emission reduction initiatives (TERIs) outside the UNFCCC have also been assessed and found to overlap (70–80%) with NDCs and be inadequate to bridge the gap between NDCs and a 2˚C pathway (Roelfsema et al., 2018). Weak and fragmented short-term policy efforts use up a large share of the long-term carbon budget before 2030–2050 (Bertram et al., 2015a; van Vuuren et al., 2016) and increase the need for the full portfolio of mitigation measures, including CDR (Clarke et al., 2014; Riahi et al., 2015; Xu and Ramanathan, 2017). Furthermore, fragmented policy scenarios also exhibit 'carbon leakage' via energy and capital markets (Arroyo-Currás et al., 2015; Kriegler et al., 2015b). A lack of integrated policy portfolios can increase the risks of trade-offs between mitigation approaches and sustainable development objectives (see Sections 2.5.3 and 5.4). However, more detailed analysis is needed about realistic (less disruptive) policy trajectories until 2030 that can strengthen near-term mitigation action and meaningfully decrease post-2030 challenges (see Section 4.4).

Whereas the policy frameworks and enabling conditions identified above pertain to the 'idealised' dimension of mitigation pathways, aspects related to 1.5°C mitigation pathways in practice are of prime importance. For example, issues related to second-best stringency levels, international cooperation, public acceptance, distributional consequences, multi-level governance, non-state actions, compliance levels, capacity building, rebound effects, linkages across highly heterogeneous policies, sustained behavioural change, finance and intra- and inter-generational issues need to be considered (Somanthan et al., 2014; Bataille et al., 2016a; Mundaca and Markandya, 2016; Baranzini et al., 2017; van den Bergh, 2017; Vogt-Schilb and Hallegatte, 2017; Chan et al., 2018; Holz et al., 2018a; Klinsky and Winkler, 2018; Michaelowa et al., 2018; Patterson et al., 2018) (see Section 4.4). Furthermore, policies interact with a wide portfolio of pre-existing policy instruments that address multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation) and deal with various market failures (e.g., information asymmetries) and behavioural aspects (e.g., heuristics) that prevent or hinder mitigation actions (Kolstad et al., 2014; Mehling and Tvinnereim, 2018). The socio-technical transition literature points to multiple complexities in real-world settings that prevent reaching 'idealised' policy conditions but at the same time can still accelerate transformative change through other co-evolutionary processes of technology and society (Geels et al., 2017; Rockström et al., 2017). Such co-processes are complex and go beyond the role of policy (including carbon pricing) and comprise the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions (Michaelowa et al., 2018; Veland et al., 2018). It is argued that large system transformations, similar to those in 1.5°C pathways, require prioritizing an evolutionary and behavioural framework in economic theory rather than an optimization or equilibrium framework as is common in current IAMs (Grubb et al., 2014; Patt, 2017). Accumulated know-how, accelerated innovation and public investment play a key role in (rapid) transitions (Geels et al., 2017; Michaelowa et al., 2018) (see Sections 4.2 and 4.4).

In summary, the emerging literature supports the AR5 on the need for integrated, robust and stringent policy frameworks targeting both the supply and demand-side of energy-economy systems (*high confidence*). Continuous ex-ante policy assessments provide learning opportunities for both policy makers and stakeholders.

[START CROSS CHAPTER BOX 5 HERE]

Cross-Chapter Box 5: Economics of 1.5°C Pathways and the Social Cost of Carbon

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Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness analysis (CEA)** and **cost-benefit analysis (CBA)**. **CEA** aims at identifying emissions pathways minimising the total mitigation costs of achieving a given warming or GHG limit (Clarke et al., 2014). **CBA** has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetised climate change damages (Boardman, 2006; Stern, 2007). A third concept, the **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change (Nordhaus, 2014; Pizer et al., 2014; Rose et al., 2017a). Negative and positive impacts are monetised, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC can be evaluated for any emissions pathway under policy consideration (Rose, 2012; NASEM, 2016, 2017).

Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal abatement cost of a metric ton of CO_2 emissions. Equating the present value of future damages and marginal abatement costs includes a number of critical value judgments in the formulation of the social welfare function (SWF), particularly in how non-market damages and the distribution of damages across countries and individuals and between current and future generations are valued (Kolstad et al., 2014). For example, since climate damages accrue to a larger extent in the farther future and can persist for many years, assumptions and approaches to determine the social discount rate (normative 'prescriptive' vs. positive 'descriptive') and social welfare function (e.g., discounted utilitarian SWF vs. undiscounted prioritarian SWF) can heavily influence CBA outcomes and associated estimates of SCC (Kolstad et al., 2014; Pizer et al., 2014; Adler and Treich, 2015; Adler et al., 2017; NASEM, 2017; Nordhaus, 2017; Rose et al., 2017a).

In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. It equals the shadow price of carbon associated with the goal which in turn can be interpreted as the willingness to pay for imposing the goal as a political constraint. Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as the exchange rate for pricing emissions of non-CO_2 GHGs controlled under internationally climate agreements (like CH_4, N_2O and fluorinated gases, see Cross-Chapter Box 1.2)[13]. Since policy goals like the goals of limiting warming to 1.5°C or well below 2°C do not directly result from a money metric trade-off between mitigation and damages, associated shadow prices can differ from the SCC in a CBA. In CEA, value judgments are to a large extent concentrated in the choice of climate goal and related implications, while more explicit assumptions about social values are required to perform CBA. For example, assumptions about the social discount rate no longer affect the overall abatement levels now set by the climate goal, but the choice and timing of investments in individual measures to reach these levels.

Although CBA-based and CEA-based assessment are both subject to large uncertainty about socio-techno-economic trends, policy developments and climate response, the range of estimates for the SCC along an optimal trajectory determined by CBA is far higher than for estimates of the shadow price of carbon in CEA-based approaches. In CBA, the value judgments about inter- and intra-generational equity combined with uncertainties in the climate damage functions assumed, including their empirical basis, are important (Pindyck, 2013; Stern, 2013; Revesz et al., 2014). In a CEA-based approach, the value judgments about the aggregate welfare function matter less and uncertainty about climate response and impacts can be tied into various climate targets and related emissions budgets (Clarke et al., 2014).

The CEA- and CBA-based carbon cost estimates are derived with a different set of tools. They are all summarised as integrated assessment models (IAMs) but in fact are of very different nature (Weyant, 2017). Detailed process IAMs such as AIM (Fujimori, 2017), GCAM (Thomson et al., 2011; Calvin et al., 2017), IMAGE (van Vuuren et al., 2011b, 2017b), MESSAGE-GLOBIOM (Riahi et al., 2011; Havlík et al., 2014; Fricko et al., 2017), REMIND-MAgPIE (Popp et al., 2010; Luderer et al., 2013; Kriegler et al., 2017) and WITCH (Bosetti et al., 2006, 2008, 2009) include a process-based representation of energy and land systems, but in most cases lack a comprehensive representation of climate damages, and are typically used for CEA. Diagnostic analyses across CBA-IAMs indicate important dissimilarities in modelling assembly, implementation issues and behaviour (e.g., parametric uncertainty, damage responses, income sensitivity) that need to be recognised to better understand SCC estimates (Rose et al., 2017a).

CBA-IAMs such as DICE (Nordhaus and Boyer, 2000; Nordhaus, 2013, 2017), PAGE (Hope, 2006) and FUND (Tol, 1999; Anthoff and Tol, 2009) attempt to capture the full feedback from climate response to socio-economic damages in an aggregated manner, but are usually much more stylised than detailed process IAMs. In a nutshell, the methodological framework for estimating SCC involves projections of population growth, economic activity and resulting emissions; computations of atmospheric composition and global-mean temperatures as a result of emissions; estimations of physical impacts of climate changes; monetisation of impacts (positive and negative) on human welfare; and the discounting of the future monetary value of impacts to year of emission (Kolstad et al., 2014; Revesz et al., 2014; NASEM, 2017; Rose et al., 2017a). There has been a discussion in the literature to what extent CBA-IAMs underestimate the SCC due to, for example, a limited treatment or difficulties in addressing damages to human well-being, labour productivity, value of capital stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and Stanton, 2012; Revesz et al., 2014; Moore and Diaz, 2015; Stern, 2016). However, there has been progress in 'bottom-up' empirical analyses of climate damages (Hsiang et al., 2017), the insights of which could be integrated into these models (Dell et al., 2014). Most of the models used in Chapter 2 on 1.5°C mitigation pathways are detailed process IAMs and thus deal with CEA.

[13] FOOTNOTE: Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar, 1995; Marten et al., 2015; Shindell, 2015; Interagency Working Group on Social Cost of Greenhouse Gases, 2016).

An important question is how results from CEA- and CBA-type approaches can be compared and synthesised. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under the climate goal and SCC estimates from CBA might not be directly comparable due to different tools, approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO_2^{-1} that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors include accounting for tipping points in the climate system (Lemoine and Traeger, 2014; Cai et al., 2015; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2005; Stern, 2007) and inequality aversion (Schmidt et al., 2013; Dennig et al., 2015; Adler et al., 2017).

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation (Pizer et al., 2014; Revesz et al., 2014; Stiglitz et al., 2017). As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz et al., 2017), in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France. Since 2008, the U.S. government has used SCC estimates to assess the benefits and costs related to CO_2 emissions resulting from federal policymaking (NASEM, 2017; Rose et al., 2017a).

The use of the SCC for policy appraisals is however not straightforward in an SDG context. There are suggestions that a broader range of polluting activities than only CO_2 emissions, for example emissions of air pollutants, and a broader range of impacts than only climate change, such as impacts on air quality, health and sustainable development in general (see Chapter 5 for a detailed discussion), would need to be included in social costs (Sarofim et al., 2017; Shindell et al., 2017a). Most importantly, a consistent valuation of the SCC in a sustainable development framework would require accounting for the SDGs in the social welfare formulation (see Chapter 5).

[END CROSS CHAPTER BOX 5 HERE]

2.5.2 Economic and financial implications of 1.5°C Pathways

2.5.2.1 Price of carbon emissions

The price of carbon assessed here is fundamentally different from the concepts of optimal carbon price in a cost-benefit analysis, or the social cost of carbon (see Cross-Chapter Box 5 in this Chapter and Section 3.5.2). Under a cost-effective analysis (CEA) modelling framework, prices for carbon (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission).

Based on data available for this special report, the price of carbon varies substantially across models and scenarios, and their value increase with mitigation efforts (see Figure 2.26) (*high confidence*). For instance, undiscounted values under a Higher-2˚C pathway range from 10–200 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2030, 45–960 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2050, 120–1000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2070 and 160–2125 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2100. On the contrary, estimates for a Below-1.5˚C pathway range from 135–5500 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2030, 245–13000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2050, 420–17500 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2070 and 690–27000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2100. One can also observe that values for 1.5°C-low-OS pathway are relatively higher than 1.5°C-high-OS pathway in 2030, but the difference decreases over time. This is because in 1.5°C-high-OS pathways there is relatively less mitigation activity in the first half of the century, but more in the second half. *LED* exhibits the lowest values across the illustrative pathway archetypes. As a whole, the average discounted price of emissions across 1.5˚C- and 2˚C pathways differs by a factor of four across models (assuming a 5% annual discount rate). If values from 1.5˚C-high-OS pathways (with peak warming 0.1–0.4°C higher than 1.5°C) or pathways with very large land-use sinks are kept in the 1.5˚C pathway superclass, the differential value is reduced to a limited degree, from a factor 4 to a factor 3. The increase in carbon prices between 1.5°C- and 2°C-consistent pathways is based on a direct comparison of pathway pairs from the same model and the same study in which the 1.5°C-consistent pathway assumes a significantly smaller carbon budget compared to the 2°C-consistent pathway (e.g., 600 $GtCO_2$ smaller in the CD-LINKS and ADVANCE studies). This assumption is the main driver behind the increase in the price of carbon (Luderer et al., 2018; McCollum et al., 2018).[14] Considering incomplete and uncertain information, an optimal price of carbon of the magnitude estimated in modelling studies needs to be compared with what is politically and institutionally feasible (see Section 4.4.5.2).

The wide range of values depends on numerous aspects, including methodologies, projected energy service demands, mitigation targets, fuel prices and technology availability (Clarke et al., 2014; Kriegler et al., 2015b; Rogelj et al., 2015c; Riahi et al., 2017; Stiglitz et al., 2017) (*high confidence*). The characteristics of the technology portfolio, particularly in terms of investment costs and deployment rates play a key role (Luderer et al., 2013, 2016a; Clarke et al., 2014; Bertram et al., 2015a; Riahi et al., 2015; Rogelj et al., 2015c). Models that encompass a higher degree of technology granularity and that entail more flexibility regarding mitigation response, often produce relatively lower mitigation costs than those that show less flexibility from a technology perspective (Bertram et al., 2015a; Kriegler et al., 2015a). Pathways providing high estimates often have limited flexibility of substituting fossil fuels with low-carbon technologies and the associated need to compensate fossil-fuel emissions with CDR. Emission prices are also sensitive to the non-availability of BECCS (Bauer et al., 2018). Furthermore, and due to the treatment of future price anticipation, recursive-dynamic modelling approaches (with 'myopic anticipation') exhibit higher prices in the short term but modest increases in the long term compared to optimisation modelling frameworks with 'perfect foresight' that show exponential pricing trajectories (Guivarch and Rogelj, 2017). The chosen social discount rate in CEA studies (range of 2–8% per year in the reported data, varying over time and sectors) can also affect the choice and timing of investments in mitigation measures (Clarke et al., 2014; Kriegler et al., 2015b; Weyant, 2017). However, the impacts of varying discount rates on 1.5°C (and 2˚C) mitigation strategies can only be assessed to a limited degree. The above highlights the importance of sampling bias in pathway analysis ensembles towards outcomes derived from models which are more flexible, have more mitigation options and cheaper cost assumptions and thus can provide feasible pathways in contrast to other who are unable to do so (Tavoni and Tol, 2010; Clarke et al., 2014; Bertram et al., 2015a; Kriegler et al., 2015a; Guivarch and Rogelj, 2017). All CEA-based IAM studies reveal no unique carbon pricing path (Bertram et al., 2015a; Kriegler et al., 2015b; Akimoto et al., 2017; Riahi et al., 2017).

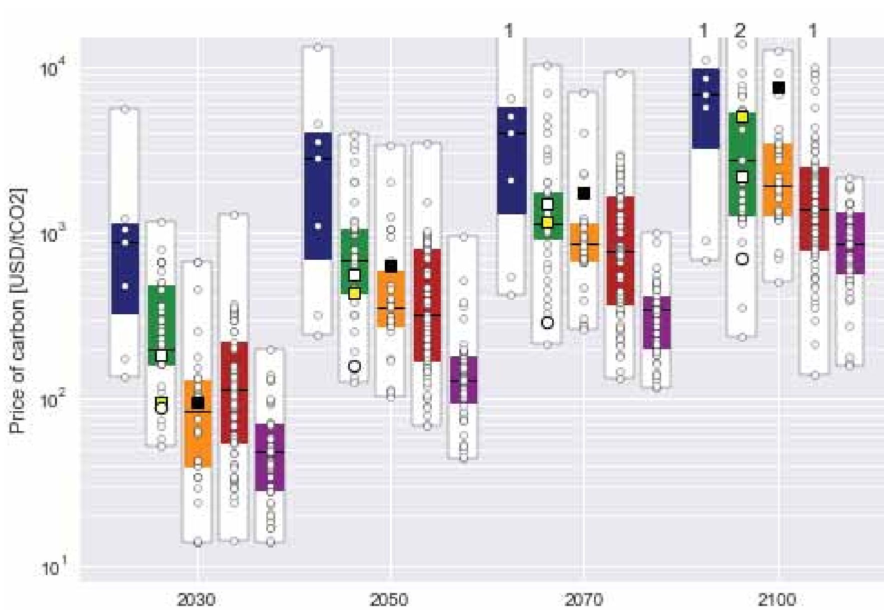
Socio-economic conditions and policy assumptions also influence the price of carbon (Bauer et al., 2017; Guivarch and Rogelj, 2017; Hof et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). A multi-model study (Riahi et al., 2017) estimated the average discounted price of carbon (2010-2100, 5% discount rate) for a 2˚C target to be nearly three times higher in the SSP5 marker than in the SSP1 marker. Another multi-model study (Rogelj et al., 2018) estimated average discounted carbon prices (2020-2100, 5%) to be 35–65% lower in SSP1 compared to SSP2 in 1.5˚C pathways. Delayed near-term mitigation policies and measures, including the limited extent of international global cooperation, increases total economic mitigation costs, and corresponding prices of carbon (Luderer et al., 2013; Clarke et al., 2014). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near term. Staged accession scenarios also produce higher carbon prices than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b). In addition, the revenue recycling effect of carbon pricing can reduce mitigation costs by displacing distortionary taxes (Baranzini et al., 2017; OECD, 2017; McFarland et al., 2018; Sands, 2018; Siegmeier et al., 2018) and the reduction of capital tax (compared to a labour tax) can yield greater savings in welfare costs (Sands, 2018). The effect on public budgets is particularly important in the near term, however it can decline in the long term as carbon neutrality is achieved (Sands, 2018).

It has been long argued that carbon pricing (whether via a tax or cap-and-trade scheme) can theoretically achieve cost-effective emission reductions (Nordhaus, 2007; Stern, 2007; Aldy and Stavins, 2012; Goulder and Schein, 2013; Somanthan et al., 2014; Weitzman, 2014; Tol, 2017). Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Riahi et al., 2017; Weyant, 2017) there is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policy mixes (e.g., regulation, subsidies, standards). Assuming global implementation of a mix of regionally existing best practice policies (mostly regulatory policies in the electricity, industry, buildings, transport and agricultural sectors) and moderate carbon pricing (between 5–

[14] FOOTNOTE: Unlike AR5, which only included cost-effective scenarios for estimating discounted average carbon prices for 2015-2100 (also using a 5% discount rate) (see Clarke et al., 2014, p.450), please note that values shown in Figure 2.26 (panel b) include delays or technology constraint cases (see Sections 2.1 and 2.3).

20 USD_{2010} tCO_2^{-1} in 2025 in most world regions and average prices around 25 USD_{2010} tCO_2^{-1} in 2030), early action mitigation pathways are generated that reduce global CO_2 emissions by an additional 10 $GtCO_2e$ in 2030 compared to the NDCs (Kriegler et al., 2018b) (see Section 2.3.5). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards, building codes) combined with a carbon tax (rising from 10 USD_{2010} tCO_2^{-1} in 2020 to 27 USD_{2010} tCO_2^{-1} in 2040) is more cost-effective than a carbon tax alone (from 20 to 53 USD_{2010} tCO_2^{-1}) to generate a 1.5˚C pathway for the U.S. electric sector (Brown and Li, 2018). Likewise, a policy mix encompassing a moderate carbon price (7 USD_{2010} tCO_2^{-1} in 2015) combined with a ban on new coal-based power plants and dedicated policies addressing renewable electricity generation capacity and electric vehicles reduces efficiency losses compared with an optimal carbon pricing in 2030 (Bertram et al., 2015b). One study estimates the price of carbon in high energy-intensive pathways to be 25–50% higher than in low energy-intensive pathways that assume ambitious regulatory instruments, economic incentives (in addition to a carbon price) and voluntary initiatives (Méjean et al., 2018). A bottom-up approach shows that stringent minimum performance standards (MEPS) for appliances (e.g., refrigerators) can effectively complement carbon pricing, as tightened MEPS can achieve ambitious efficiency improvements that cannot be assured by carbon prices of 100 USD_{2010} tCO_2^{-1} or higher (Sonnenschein et al., 2018). The literature indicates that the pricing of emissions is relevant but needs to be complemented with other policies to drive the required changes in line with 1.5°C-consistent cost-effective pathways (Stiglitz et al., 2017; Mehling and Tvinnereim, 2018; Méjean et al., 2018; Michaelowa et al., 2018) (*low to medium evidence*, *high agreement*) (see Section 4.4.5).

In summary, new analyses are consistent with the AR5 and show that the price of carbon would need to increase significantly when a higher level of stringency is pursued (*high confidence*). Values vary substantially across models, scenarios and socio-economic, technology and policy assumptions. While the price of carbon is central to prompt mitigation pathways compatible with 1.5°C-consistent pathways, a complementary mix of stringent policies is required.



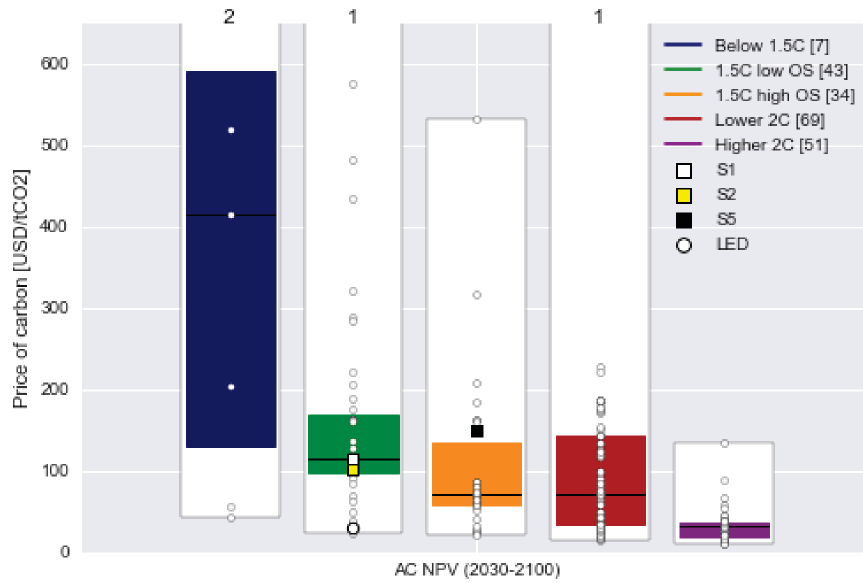


Figure 2.26: Global price of carbon emissions consistent with mitigation pathways. Panels show undiscounted price of carbon (2030-2100) (top panel) and average price of carbon (2030-2100) discounted at a 5% discount rate (lower panel). AC: Annually compounded. NPV: Net present value. Median values in floating black line. The number of pathways included in boxplots is indicated in the legend. Number of pathways outside the figure range is noted at the top.

2.5.2.2 Investments

Realising the transformations towards a 1.5°C world requires a major shift in investment patterns (McCollum et al., 2018). Literature on global climate-change mitigation investments is relatively sparse, with most detailed literature having focused on 2°C pathways (McCollum et al., 2013; Bowen et al., 2014; Gupta and Harnisch, 2014; Marangoni and Tavoni, 2014; OECD/IEA and IRENA, 2017).

Global energy-system investments in the year 2016 are estimated at approximately 1.7 trillion USD_{2010} (approximately 2.2% of global GDP and 10% of gross capital formation), of which 0.23 trillion USD_{2010} was for incremental end-use energy efficiency and the remainder for supply-side capacity installations (IEA, 2017c). There is some uncertainty surrounding this number because not all entities making investments report them publicly, and model-based estimates show an uncertainty range of about ± 15% (McCollum et al., 2018). Notwithstanding, the trend for global energy investments has been generally upward over the last two decades: increasing about threefold between 2000 and 2012, then levelling off for three years before declining in both 2015 and 2016 as a result of the oil price collapse and simultaneous capital cost reductions for renewables (IEA, 2017c).

Estimates of demand-side investments, either in total or for incremental efficiency efforts, are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment and what the reference should be for estimating incremental efficiency (McCollum et al., 2013). Grubler and Wilson (2014) use two working definitions (a broader and a narrower one) to provide a first-order estimate of historical end-use technology investments in total. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies (e.g., compressor, car engine, heating element). Based on these two definitions, demand-side energy investments for the year 2005 were estimated about 1–3.5 trillion USD_{2010} (central estimate 1.7 trillion USD_{2010}) using the broad definition and 0.1–0.6 trillion USD_{2010} (central estimate 0.3 trillion USD_{2010}) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare. Global IAMs often do not fully and explicitly represent all the various measures that could improve end-use efficiency.

Research carried out by six global IAM teams found that 1.5°C-consistent climate policies would require a marked upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage) between now and mid-century, reaching levels of between 1.6–3.8 trillion USD_{2010} yr^{-1} globally on average over the 2016-2050 timeframe (McCollum et al., 2018) (Figure 2.27). How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, much higher, or lower. Investments in the policy baselines from these same models are 1.6–2.7 trillion USD_{2010} yr^{-1}. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al., 2018) and in some cases up to 50% (Grubler et al., 2018) if strong policies to limit energy demand growth are successfully implemented. However, the degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is unclear.

Some trends are robust across scenarios (Figure 2.27). First, pursuing 1.5°C mitigation efforts requires a major reallocation of the investment portfolio, implying a financial system aligned to mitigation challenges. The path laid out by countries' current NDCs until 2030 will not drive these structural changes; and despite increasing low-carbon investments in recent years (IEA, 2016b; Frankfurt School-UNEP Centre/BNEF, 2017), these are not yet aligned with 1.5°C. Specifically, annual investments in low-carbon energy are projected to average 0.8–2.9 trillion USD_{2010} yr^{-1} globally to 2050 in 1.5 °C pathways, overtaking fossil investments globally already by around 2025 (McCollum et al., 2018). The bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1.0 trillion USD_{2010} yr^{-1} and 0.1–0.35 trillion USD_{2010} yr^{-1}, respectively) as well as nuclear power (0.1–0.25 trillion USD_{2010} yr^{-1}). The precise apportioning of these investments depends on model assumptions and societal preferences related to mitigation strategies and policy choices (see Sections 2.1 and 2.3). Investments for electricity transmission and distribution and storage are also scaled up in 1.5°C pathways (0.3–1.3 trillion USD_{2010} yr^{-1}), given their widespread electrification of the end-use sectors (see Section 2.4). Meanwhile, 1.5°C pathways see a reduction in annual investments for fossil-fuel extraction and unabated fossil electricity generation (to 0.3–0.85 trillion USD_{2010} yr^{-1} on average over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C projections, while the literature is less conclusive for investments in unabated gas (McCollum et al., 2018). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Section 2.5.3). Furthermore, some fossil investments made over the next few years – or those made in the last few – will likely need to be retired prior to fully recovering their capital investment or before the end of their operational lifetime (Bertram et al., 2015a; Johnson et al., 2015; OECD/IEA and IRENA, 2017). How the pace of the energy transition will be affected by such dynamics, namely with respect to politics and society, is not well captured by global IAMs at present. Modelling studies have, however, shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al., 2015), finding that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016).

Low-carbon supply-side investment needs are projected to be largest in OECD countries and those of developing Asia. The regional distribution of investments in 1.5°C pathways estimated by the multiple models in (McCollum et al., 2018) are the following (average over 2016-2050 timeframe): 0.30-1.3 trillion USD_{2010} yr^{-1}(ASIA), 0.35–0.85 trillion USD_{2010} yr^{-1} (OECD), 0.08–0.55 trillion USD_{2010} yr^{-1} (MAF), 0.07–0.25 trillion USD_{2010} yr^{-1} (LAM), and 0.05–0.15 trillion USD_{2010} yr^{-1} (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

Until now, IAM investment analyses of 1.5 °C pathways have focused on middle-of-the-road socioeconomic and technological development futures (SSP2) (Fricko et al., 2017). Consideration of a broader range of development futures would yield different outcomes in terms of the magnitudes of the projected investment levels. Sensitivity analyses indicate that the magnitude of supply-side investments as well as the investment portfolio do not change strongly across the SSPs for a given level of climate policy stringency (McCollum et al., 2018). With only one dedicated multi-model comparison study published, there is *limited to medium evidence* available. For some features, there is *high agreement* across modelling frameworks leading, for example, to *medium to high confidence* that limiting global temperature increase to 1.5°C will require a major reallocation of the investment portfolio. Given the limited amount of sensitivity cases available compared to the default SSP2 assumptions, *medium confidence* can be assigned to the specific energy and climate mitigation investment estimates reported here.

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilisation of funds are critical (Fankhauser et al., 2016; OECD, 2017). In turn, policy efforts need to be effective in re-directing financial resources (UNEP, 2015; OECD, 2017) and reduce transaction costs for bankable mitigation projects (i.e. projects that have adequate future cash-flow, collateral, etc. so lenders are willing to finance it), particularly on the demand side (Mundaca et al., 2013; Brunner and Enting, 2014; Grubler et al., 2018). Assumptions also imply that policy certainty, regulatory oversight mechanisms and fiduciary duty need to be robust and effective to safeguard credible and stable financial markets and de-risk mitigation investments in the long term (Clarke et al., 2014; Mundaca et al., 2016; EC, 2017; OECD, 2017). Importantly, the different time horizons that actors have in the competitive finance industry are typically not explicitly captured by modelling assumptions (Harmes, 2011). See Section 4.4.5 for details of climate finance in practice.

In summary and despite inherent uncertainties, the emerging literature indicates a gap between current investment patterns and those compatible with 1.5°C (or 2°C) pathways (*limited to medium evidence, high agreement*). Estimates and assumptions from modelling frameworks suggest a major shift in investment patterns and entail a financial system effectively aligned with mitigation challenges (*high confidence*).

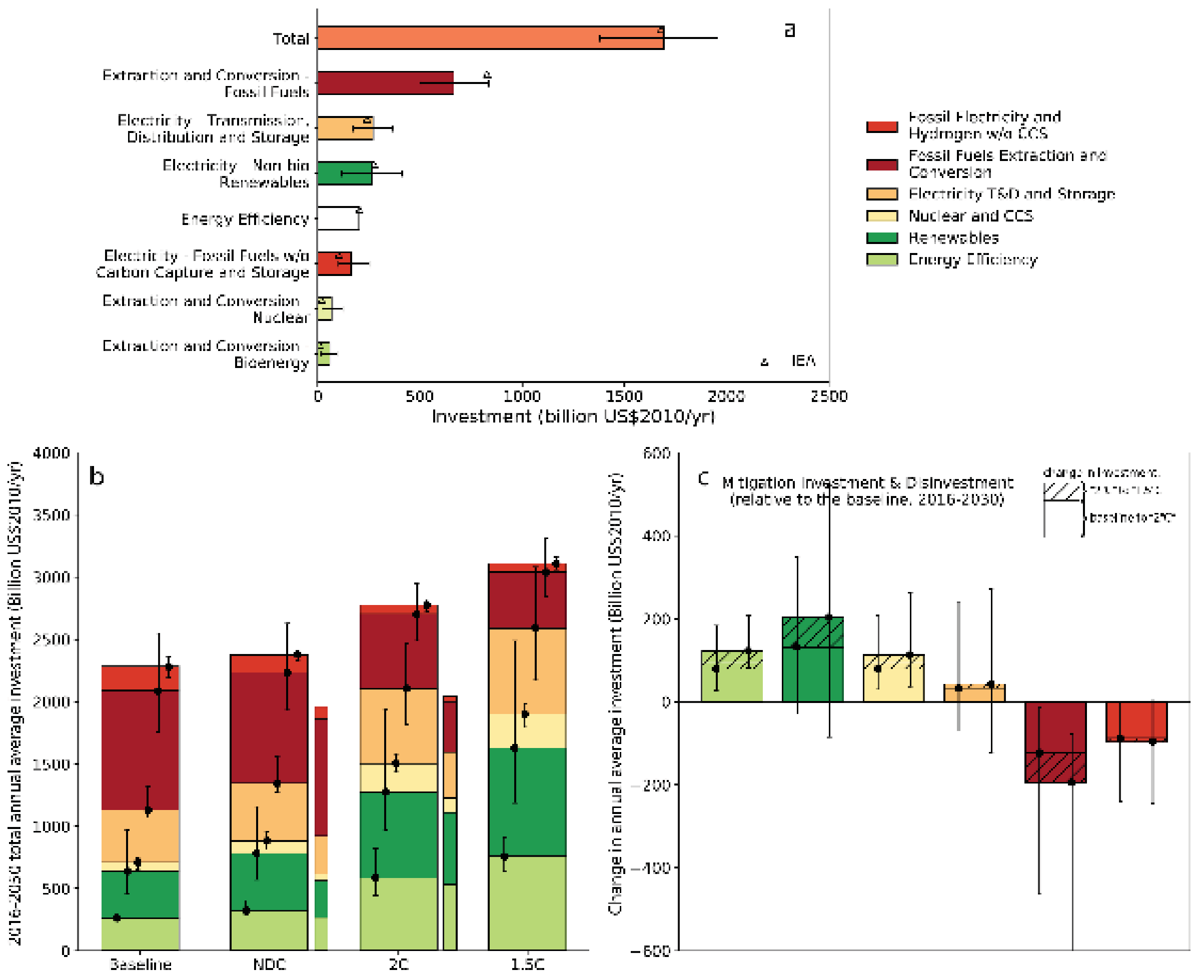


Figure 2.27: Historical and projected global energy investments. (a) Historical investment estimates across six global models from (McCollum et al., 2018) (bars = model means, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (triangles). (b) Average annual investments over the 2016–2050 period in no-climate policy 'baselines', scenarios which implement the NDCs ('NDC'), scenarios consistent with the Lower-2°C pathway class ('2°C'), and scenarios in line with the 1.5°C-low-OS pathway class ('1.5°C'). Whiskers show the range of models; wide bars show the multi-model means; narrow bars represent analogous values from individual IEA

scenarios (OECD/IEA and IRENA, 2017). (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for '2°C' pathways, while the hatched areas show the additional investments for the pathways labelled with '1.5°C'. Whiskers show the full range around the multi-model means. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage. Global cumulative carbon dioxide emissions, from fossil fuels and industrial processes (FF&I) but excluding land use, over the 2016-2100 timeframe range from 880 to 1074 $GtCO_2$ (multi-model mean: 952 $GtCO_2$) in the '2°C' pathway and from 206 to 525 $GtCO_2$ (mean: 390 $GtCO_2$) in the '1.5°C' pathway.

2.5.3 Sustainable development features of 1.5°C pathways

Potential synergies and trade-offs between 1.5°C mitigation pathways and different sustainable development (SD) dimensions (see Cross-Chapter Box 4) are an emerging field of research. Section 5.4 assesses interactions between individual mitigation measures with other societal objectives, as well as the Sustainable Development Goals (SGDs) (Table 5.1). This section synthesized the Chapter 5 insights to assess how these interactions play out in integrated 1.5°C pathways, and the four illustrative pathway archetypes of this chapter in particular (see Section 2.1). Information from integrated pathways is combined with the interactions assessed in Chapter 5 and aggregated for each SDG, with a level of confidence attributed to each interaction based on the amount and agreement of the scientific evidence (see Chapter 5).

Figure 2.28 shows how the scale and combination of individual mitigation measures (i.e., their mitigation portfolios) influence the extent of synergies and trade-offs with other societal objectives. All pathways generate multiple synergies with SD dimensions and can advance several other SDGs simultaneously. Some, however, show higher risks for trade-offs. An example is increased biomass production and its potential to increase pressure on land and water resources, food production, biodiversity, and reduced air-quality when combusted inefficiently. At the same time, mitigation actions in energy-demand sectors and behavioural response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions (see Section 5.4, Table 5.1 and Figure 5.3 for more examples). Of the four pathway archetypes used in this chapter (*S1*, *S2*, *S5*, and *LED*), the *S1* and *LED* pathways show the largest number of synergies and least number of potential trade-offs, while for the *S5* pathway most potential trade-offs are identified. In general, pathways with emphasis on demand reductions, with policies that incentivise behavioural change, sustainable consumption patterns, healthy diets and relatively low use of CDR (or only afforestation) show relatively more synergies with individual SDGs than others.

There is *robust evidence* and *high agreement* in the pathway literature that multiple strategies can be considered to limit warming to 1.5°C (see Sections 2.1.3, 2.3 and 2.4). Together with the extensive evidence on the existence of interactions of mitigation measures with other societal objectives (Section 5.4), this results in *high confidence* that the choice of mitigation portfolio or strategy can markedly affect the achievement of other societal objectives. For instance, action on SLCFs has been suggested to facilitate the achievement of SDGs (Shindell et al., 2017b) and to reduce regional impacts, e.g., from black carbon sources on snow and ice loss in the Arctic and alpine regions (Painter et al., 2013), with particular focus on the warming sub-set of SLCFs. Reductions in both surface aerosols and ozone through methane reductions provide health and ecosystem co-benefits (Jacobson, 2002, 2010; Anenberg et al., 2012; Shindell et al., 2012; Stohl et al., 2015; Collins et al., 2018). Public health benefits of stringent mitigation pathways in line with 1.5°C-consistent pathways can be sizeable. For instance, a study examining a more rapid reduction of fossil-fuel usage to achieve 1.5°C relative to 2°C, similar to that of other recent studies (Grubler et al., 2018; van Vuuren et al., 2018), found that improved air quality would lead to more than 100 million avoided premature deaths over the 21st century (Shindell et al., 2018). These benefits are assumed to be in addition to those occurring under 2°C pathways (e.g., Silva et al., 2016), and could in monetary terms offset a large portion to all of the initial mitigation costs (West et al., 2013; Shindell et al., 2018). However, some sources of SLCFs with important impacts for public health (e.g., traditional biomass burning) are only mildly affected by climate policy in the available integrated pathways and are more strongly impacted by baseline assumptions about future societal development and preferences, and technologies instead (Rao et al., 2016, 2017).

At the same time, the literature on climate-SDG interactions is still an emergent field of research and hence there is *low to medium confidence* in the precise magnitude of the majority of these interactions. Very limited literature suggests that achieving co-benefits are not automatically assured but result from conscious and carefully coordinated policies and implementation strategies (Shukla and Chaturvedi, 2012; Clarke et al., 2014; McCollum et al., 2018). Understanding these mitigation-SDG interactions is key for selecting mitigation options that maximise synergies and minimize trade-offs towards the 1.5°C and sustainable development objectives (van Vuuren et al., 2015; Hildingsson and Johansson, 2016; Jakob and Steckel, 2016; von Stechow et al., 2016; Delponte et al., 2017).

In summary, the combined evidence indicates that the chosen mitigation portfolio can distinctly have an impact on the achievement of other societal policy objectives (*high confidence*); however, there is uncertainty regarding the specific extent of climate-SDG interactions.

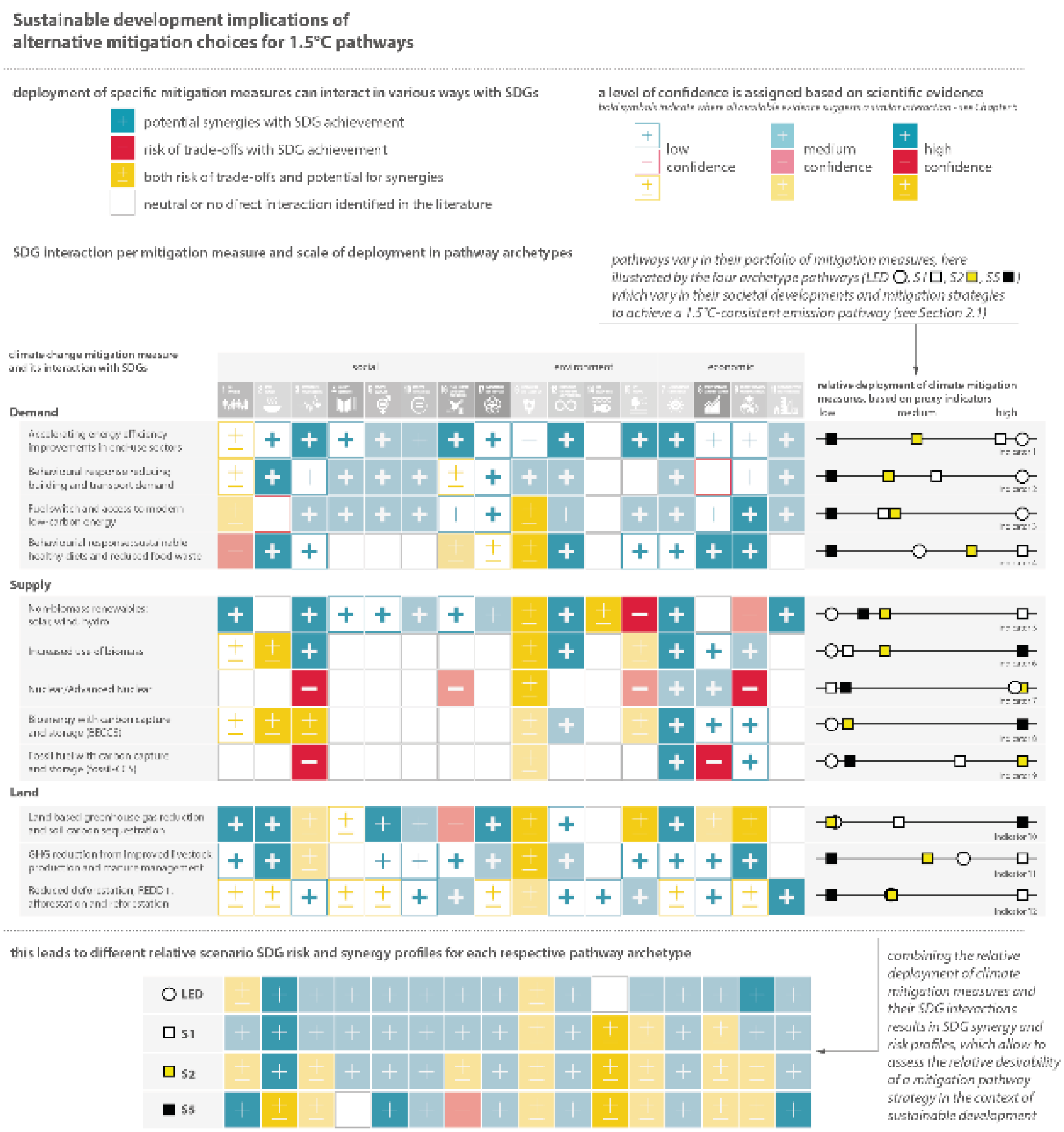


Figure 2.28: Interactions of individual mitigation measures and alternative mitigations portfolios for 1.5°C with Sustainable Development Goals (SDGs). The assessment of interactions between mitigation measures and individual SDGs is based on the assessment of Section 5.4. Proxy indicators and synthesis method are described in Annex 2.A.5.

2.6 Knowledge gaps

This section summarises the knowledge gaps articulated in earlier sections of the chapter.

2.6.1 Geophysical understanding

Knowledge gaps are associated with the carbon-cycle response, the role of non-CO_2 emissions and on the evaluation of an appropriate historic baseline.

Quantifying how the carbon cycle responds to negative emissions is an important knowledge gap for strong mitigation pathways (Section 2.2). Earth-system feedback uncertainties are important to consider for the longer-term response, particularly in how permafrost melting might affect the carbon budget (Section 2.2). Future research and ongoing observations over the next years will provide a better indication as to how the 2006-2015 base period compares with the long-term trends and might at present bias the carbon budget estimates.

The future emissions of short-lived climate forcers and their temperature response are a large source of uncertainty in 1.5°C pathways, having a greater relative uncertainty than in higher CO_2 emission pathways. Their global emissions, their sectorial and regional disaggregation and their climate response are generally less well quantified than for CO_2 (Sections 2.2 and 2.3). Emissions from the agricultural sector including land-use based mitigation options in 1.5°C pathways constitute the main source of uncertainty here and are an important gap in understanding the potential achievement of stringent mitigation scenarios (Sections 2.3 and 2.4). This also includes uncertainties surrounding the mitigation potential of the long-lived GHG nitrous oxide. (Sections 2.3 and 2.4)

There is considerable uncertainty in how future emissions of aerosol precursors will affect the effective radiative forcing from aerosol-cloud interaction. The potential future warming from mitigation of these emissions reduces remaining carbon budgets and increases peak temperatures (Section 2.2). The potential co-benefits of mitigating air pollutants and how the reduction in air pollution may affect the carbon sink are also important sources of uncertainty (Sections 2.2 and 2.5).

The pathway classification employed in this Chapter employs results from the MAGICC model with its AR5 parameter sets. The alternative representation of the relationship between emissions and effective radiative forcing and response in the FAIR model would lead to a different classification that would make 1.5°C targets more achievable (Section 2.2 and Annex 2.A.1). Such a revision would significantly alter the temperature outcomes for the pathways and, if the result is found to be robust, future research and assessments would need to adjust their classifications accordingly. Any possible high bias in the MAGICC response may be partly or entirely offset by missing Earth system feedbacks that are not represented in either climate emulator that would act to increase the temperature response (Section 2.2). For this assessment report, any possible bias in MAGICC setup applied in this and earlier reports is not established enough in the literature to change the classification approach. However, we only place *medium confidence* in the classification adopted by the chapter.

2.6.2 Integrated assessment approaches

IAMs attempt to be as broad as possible in order to explore interactions between various societal subsystems, like the economy, land, and energy system. They hence include stylised and simplified representations of these subsystems. Climate damages, avoided impacts and societal co-benefits of the modelled transformations remain largely unaccounted for and are important knowledge gaps. Furthermore, rapid technological changes and uncertainties about input data present continuous challenges.

The IAMs used in this report do not account for climate impacts (Section 2.1), and similarly, none of the Gross Domestic Product (GDP) projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Section 2.3). Although some IAMs do allow for climate impact feedbacks in their modelling frameworks, particularly in their land components, such feedbacks were by design excluded in pathways developed in the context of the SSP framework. The SSP framework aims at providing an integrative framework for the assessment of climate change adaptation and mitigation. IAMs are typically developed to inform the mitigation component of this question, while the assessment of impacts is carried out by specialized impact models. However, the use of a consistent set of socio-economic drivers embodied by the SSPs allows for an integrated assessment of climate change impacts and mitigation challenges at a later stage. Further integration of these two strands of research will allow a better understanding of climate impacts on mitigation studies.

Many of the IAMs that contributed mitigation pathways to this assessment include a process-based description of the land system in addition to the energy system and several have been extended to cover air pollutants and water use. These features make them increasingly fit to explore questions beyond those that touch upon climate mitigation only. The models do not, however, fully account for all constraints that could affect realization of pathways (Section 2.1).

While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in that realized by selected pathways from IAMs, indicating the possibility to strengthen sectorial decarbonisation strategies compared to the IAM 1.5°C pathways assessed in this chapter (Section 2.1).

Studies indicate that a major shift in investment patterns is required to limit global warming to 1.5°C. This assessment would benefit from a more explicit representation and understanding of the financial sector within the modelling approaches. Assumptions in modelling studies imply low-to-zero transaction costs for market agents and that regulatory oversight mechanisms and fiduciary duty need to be highly robust to guarantee stable and credible financial markets in the long term. This area can be subject to high uncertainty, however. The heterogeneity of actors (e.g., banks, insurance companies, asset managers, or credit rating agencies) and financial products also needs to be taken into account, as does the mobilisation of capital and financial flows between countries and regions (Section 2.5).

The literature on interactions between 1.5˚C mitigation pathways and SDGs is an emergent field of research (Section 2.3.5, 2.5 and Chapter 5). Whereas the choice of mitigation strategies can noticeably affect the attainment of various societal objectives, there is uncertainty regarding the extent of the majority of identified interactions. Understanding climate-SDG interactions helps the choice of mitigation options that minimize trade-offs and risks and maximise synergies towards sustainable development objectives and the 1.5°C goal (Section 2.5).

2.6.3 Carbon Dioxide Removal (CDR)

Most 1.5°C and 2°C pathways are heavily reliant on CDR at a speculatively large scale before mid-century. There are a number of knowledge gaps associated which such technologies. Chapter 4 performs a detailed assessment of CDR technologies.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Section 4.2.7). Technologies other than BECCS and afforestation have yet to be comprehensively assessed in integrated assessment approaches. No proposed technology is close to deployment at scale and regulatory frameworks are not established. This limits how they can be realistically implemented within IAMs. (Section 2.3)

Evaluating the potential from BECCS is problematic due to large uncertainties in future land projections due to differences in modelling approaches in current land-use models which are at least as great as the differences attributed to climate scenario variations. (Section 2.3)

There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals. It is not fully understood how land use and land management choices for large-scale BECCS will affect various ecosystem services and sustainable development, and further translate into indirect impacts on climate including GHG emissions other than CO_2. (Section 2.3, Section 2.5.3)

Frequently Asked Questions

FAQ 2.1: What kind of pathways limit warming to 1.5°C and are we on track?

***Summary**: There is no definitive way to limit global temperature rise to 1.5°C above pre-industrial levels. This Special Report identifies two main conceptual pathways to illustrate different interpretations. One stabilises global temperature at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down. Countries' pledges to reduce their emissions are currently not in line with limiting global warming to 1.5°C.*

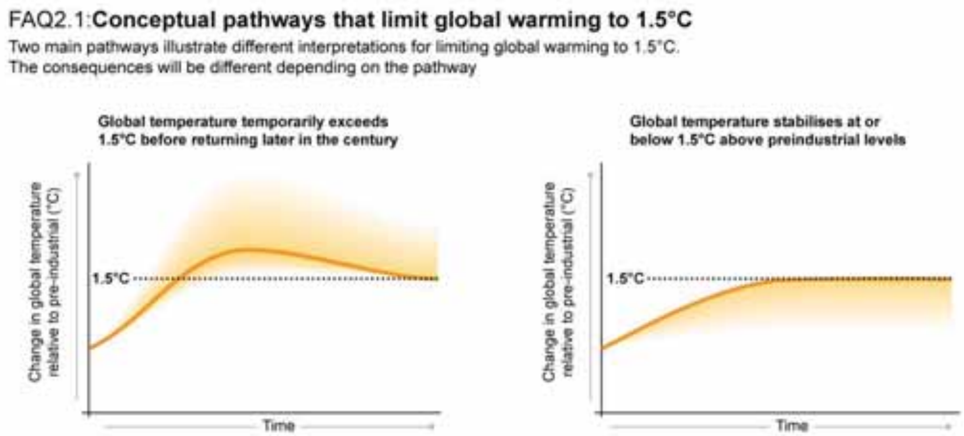
Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

This IPCC special report identifies two main pathways that explore global warming of 1.5°C. The first involves global temperature stabilising at or below before 1.5°C above preindustrial levels. The second pathway sees warming exceed 1.5°C around mid-century, remain above 1.5°C for a maximum duration of a few decades, and return to below 1.5°C before 2100. The latter is often referred to as an 'overshoot' pathway. Any alternative situation in which global temperature continues to rise, exceeding 1.5°C permanently until the end of the 21st century, is not considered to be a 1.5°C pathway.

The two types of pathway have different implications for greenhouse gas emissions, as well as for climate change impacts and for achieving sustainable development. For example, the larger and longer an 'overshoot', the greater the reliance on practices or technologies that remove CO_2 from the atmosphere, on top of reducing the sources of emissions (mitigation). Such ideas for CO_2 removal have not been proven to work at scale and, therefore, run the risk of being less practical, effective or economical than assumed. There is also the risk that the use of CO_2 removal techniques ends up competing for land and water and if these trade-offs are not appropriately managed, they can adversely affect sustainable development. Additionally, a larger and longer overshoot increases the risk for irreversible climate impacts, such as the onset of the collapse of polar ice shelves and accelerated sea level rise.

Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C. This, in turn, suggests that with the national pledges as they stand, warming would exceed 1.5°C, at least for a period of time, and practices and technologies that remove CO_2 from the atmosphere at a global scale would be required to return warming to 1.5°C at a later date.

A world that is consistent with holding warming to 1.5°C would see greenhouse gas emissions rapidly decline in the coming decade, with strong international cooperation and a scaling up of countries' combined ambition beyond current NDCs. In contrast, delayed action, limited international cooperation, and weak or fragmented policies that lead to stagnating or increasing greenhouse gas emissions would put the possibility of limiting global temperature rise to 1.5°C above pre-industrial levels out of reach.



FAQ2.1, Figure 1: Two main pathways for limiting global temperature rise to 1.5°C above pre-industrial levels are discussed in this Special Report. These are: stabilising global temperature at, or just below, 1.5°C (left) and global temperature temporarily exceeding 1.5°C before coming back down later in the century (right). Temperatures shown are relative to pre-industrial but pathways are illustrative only, demonstrating conceptual not quantitative characteristics.

FAQ 2.2: What do energy supply and demand have to do with limiting warming to 1.5°C?

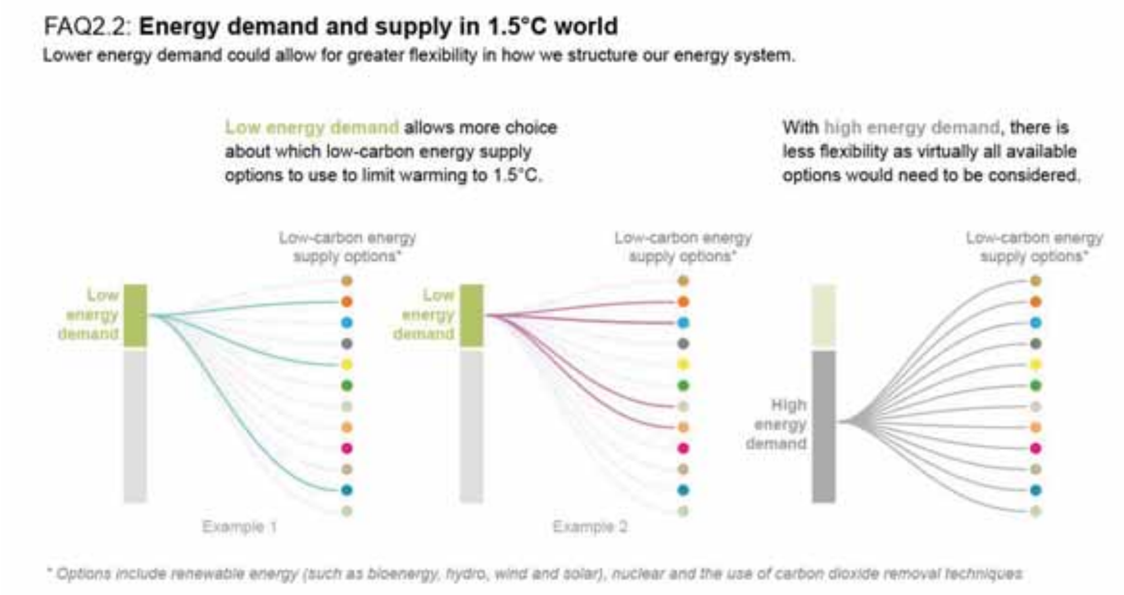
***Summary**: Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other and making changes in one can have implications for another. For example, if we as a society use a lot of energy, then this could mean we have less flexibility in the choice of mitigation options available to limit warming to 1.5°C. If we use less energy, the choice of possible actions is greater. For example we could be less reliant on technologies that remove carbon dioxide (*CO_2*) from the atmosphere.*

To stabilise global temperature at any level, 'net' CO_2 emissions would need to be reduced to zero. This means the amount of CO_2 entering the atmosphere must equal the amount that is removed. Achieving a balance between CO_2 'sources' and 'sinks' is often referred to as 'net zero' emissions or 'carbon neutrality'. The implication of net zero emissions is that the concentration of CO_2 in the atmosphere would slowly decline over time until a new equilibrium is reached, as CO_2 emissions from human activity are redistributed and taken up by the oceans and the land biosphere. This would lead to a near-constant global temperature over many centuries.

Warming will not be limited to 1.5°C or 2°C unless transformations in a number of areas achieve the required greenhouse gas emissions reductions. Emissions would need to decline rapidly across all of society's main sectors, including buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU). Actions that can reduce emissions include, for example, phasing out coal in the energy sector, increasing the amount of energy produced from renewable sources, electrifying transport, and reducing the 'carbon footprint' of the food we consume.

The above are examples of 'supply-side' actions. Broadly speaking, these are actions that can reduce greenhouse gas emissions through the use of low-carbon solutions. A different type of action can reduce how much energy human society uses, while still ensuring increasing levels of development and well-being. Known as 'demand-side' actions, this category includes improving energy efficiency in buildings and reducing consumption of energy- and greenhouse-gas intensive products through behavioural and lifestyle changes, for example. Demand and supply-side measures are not an either-or question, they work in parallel with each other. But emphasis can be given to one or the other.

Making changes in one sector can have consequences for another, as they are not independent of each other. In other words, the choices that we make now as a society in one sector can either restrict or expand our options later on. For example, a high demand for energy could mean we would need to deploy almost all known options to reduce emissions in order to limit global temperature rise to 1.5°C above pre-industrial levels, with the potential for adverse side-effects. For example, a high-demand pathway increases our reliance on practices and technologies that remove CO_2 from the atmosphere. As of yet, such techniques have not been proven to work on a large scale and, depending on how they are implemented, could compete for land and water. By leading to lower overall energy demand, effective demand-side measures could allow for greater flexibility in how we structure our energy system. However, demand-side measures are not easy to implement and barriers have prevented the most efficient practices being used in the past.



FAQ2.2, Figure 1: Having a lower energy demand increases the flexibility in choosing options for supplying energy. A larger energy demand means many more low carbon energy supply options would need to be used.

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Chapter 3: Impacts of 1.5ºC global warming on natural and human systems

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Executive Summary

This chapter builds on findings of the AR5 and assesses new scientific evidence of changes in the climate system and the associated impacts on natural and human systems, with a specific focus on the magnitude and pattern of risks for global warming of 1.5°C above the pre-industrial period. Chapter 3 explores observed impacts and projected risks for a range of natural and human systems with a focus on how risk levels change at 1.5ºC and 2ºC. The chapter also revisits major categories of risk (Reasons for Concern) based on the assessment of the new knowledge available since the AR5.

1.5°C and 2°C warmer worlds

The global climate has changed relative to the preindustrial period with multiple lines of evidence that these changes have had impacts on organisms and ecosystems, as well as human systems and well-being (*high confidence*). The increase in global mean surface temperature (GMST), which reached 0.87°C in 2006-2015 relative to 1850-1900, has increased the frequency and magnitude of impacts (*high confidence*), strengthening evidence of how increasing GMST to 1.5°C or higher could impact natural and human systems (1.5°C versus 2°C) {3.3.1, 3.3, 3.4, 3.5, 3.6, Cross-Chapter Boxes 6, 7 and 8 in this Chapter}.

Human-induced global warming has already caused multiple observed changes in the climate system (*high confidence*). In particular this includes increases in both land and ocean temperatures, as well as more frequent heatwaves in most land regions (*high confidence*). There is also *high confidence* that it has caused an increase in the frequency and duration of marine heatwaves. Further, there is evidence that global warming has led to an increase in the frequency, intensity and/or amount of heavy precipitation events at global scale (*medium confidence*), as well as having increased the risk of drought in the Mediterranean region (*medium confidence*) {3.3.1, 3.3.2, 3.3.3, 3.3.4}.

Changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred (*high confidence*). The observed tendencies over that time frame are consistent with attributed changes since the mid-20th century (*high confidence*) {3.3.1, 3.3.2, 3.3.3}.

There is no single '1.5°C warmer world' (*high confidence*). Important aspects to consider (beside that of global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of global surface temperature at 1.5°C is achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks (*high confidence*). Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (*high confidence*). The rate of change for several types of risks may also have relevance with potentially large risks in case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later (*medium confidence*). If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions is very small, which implies that large, immediate, and unprecedented global efforts to mitigate greenhouse gases are required (*high confidence*) {Cross-Chapter Box 8 in this Chapter; Sections 3.2 and 3.6.2}.

Substantial global differences in temperature and extreme events are expected if GMST reaches 1.5°C versus 2°C above the preindustrial period (*high confidence*). Regional surface temperature means and extremes are higher at 2°C as compared to 1.5°C for oceans in near all locations *(high confidence)*. Temperature means and extremes are higher at 2°C as compared to 1.5°C global warming in near all inhabited land regions, and display in some regions 2-3 times greater warming when compared to the GMST (*high confidence*). There are also substantial increases in temperature means and extremes at 1.5°C versus present (*high confidence*) {3.3.1, 3.3.2}. There are decreases in the occurrence of cold extremes, but substantial increases in their temperature {3.3.1}.

Substantial changes in regional climate occur between 1.5°C and 2°C global warming (*high confidence*), depending on the variable and region in question *(high confidence)*. Particularly large differences are found for temperature extremes *(high confidence)*. Hot extremes display the strongest warming in mid-latitudes in the warm season (with increases of up to 3°C at 1.5°C of warming, i.e. a factor of two) and cold extremes at high-latitudes in the cold season (with increases of up to 4.5°C at 1.5°C of warming, i.e. a factor of three) (*high confidence*). The strongest warming of hot extremes is found in Central and Eastern North America, Central and Southern Europe, the Mediterranean region (including Southern Europe, Northern Africa and the near-East), Western and Central Asia, and Southern Africa (*medium confidence*). The number of highly unusual hot days increase the most in the tropics, where inter-annual temperature variability is lowest; the emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2°C could result in around 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (*medium confidence*) {3.3.1, 3.3.2, Cross-Chapter Box 8 in this Chapter}.

Limiting global warming to 1.5°C limits risks of increases in heavy precipitation events in several regions (*high confidence*). The regions with the largest increases in heavy precipitation events for 1.5°C to 2°C global warming include several high-latitude regions such as Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, northern Asia; mountainous regions (e.g. Tibetan Plateau); as well as Eastern Asia (including China and Japan) and in Eastern North America (*medium confidence*). {3.3.3}. Tropical cyclones are projected to increase in intensity (with associated increases in heavy precipitation) although not in frequency (*low confidence*, *limited evidence*) {3.3.3, 3.3.6}.

Limiting global warming to 1.5°C is expected to substantially reduce the probability of drought and risks associated with water availability (i.e. water stress) in some regions (*medium confidence*). In particular, risks associated with increases in drought frequency and magnitude are substantially larger at 2°C than at 1.5°C in the Mediterranean region (including Southern Europe, Northern Africa, and the Near-East) and Southern Africa (*medium confidence*) {3.3.4, Box 3.1, Box 3.2}.

Risks to natural and human systems are lower at 1.5ºC than 2ºC *(high confidence)*. This is owing to the smaller rates and magnitudes of climate change, including reduced frequencies and intensities of temperature-related extremes. Reduced rates of change enhance the ability of natural and human systems to adapt, with substantial benefits for a range of terrestrial, wetland, coastal and ocean ecosystems (including coral reefs and wetlands), freshwater systems, as well as food production systems, human health, tourism, energy systems, and transportation {3.3.1, 3.4}.

Some regions are projected to experience multiple compound climate-related risks at 1.5°C that will increase with warming of 2°C and higher (*high confidence*). Some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards. Multi-sector risks are projected to overlap spatially and temporally, creating new (and exacerbating current) hazards, exposures, and vulnerabilities that will affect increasing numbers of people and regions with additional warming. Small island states and economically disadvantaged populations are particularly at risk. {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}.

There is *medium confidence* that a global warming of 2°C would lead to an expansion of areas with significant increases in runoff as well as those affected by flood hazard, as compared to conditions at 1.5°C global warming. A global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) as well as an increase in flood hazard in some regions (*medium confidence*) when compared to present-day conditions {3.3.5}.

There is *high confidence* that the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C when compared to 1.5°C. It is *very likely* that there will be at least one sea-ice-free Arctic summer out of 10 years for warming at 2°C, with the frequency decreasing to one sea-ice-free Arctic summer every 100 years at 1.5°C. There is also *high confidence* that an intermediate temperature overshoot will have no long-term consequences for Arctic sea-ice coverage and that hysteresis behaviour is not expected {3.3.8, 3.4.4.7}.

Global mean sea level rise will be around 0.1 m less by the end of the century in a 1.5°C world as compared to a 2°C warmer world (*medium confidence*). Reduced sea level rise could mean that up to 10.4 million fewer people (based on the 2010 global population and assuming no adaptation) are exposed to the impacts of sea level globally in 2100 at 1.5°C as compared to 2°C {3.4.5.1}. A slower rate of sea level rise enables greater opportunities for adaptation (*medium confidence*) {3.4.5.7}. There is *high confidence* that sea level rise will continue beyond 2100. Instabilities exist for both the Greenland and Antarctic ice sheets that could result in multi-meter rises in sea level on centennial to millennial timescales. There is medium confidence that these instabilities could be triggered under 1.5° to 2°C of global warming {3.3.9, 3.6.3}.

The ocean has absorbed about 30% of the anthropogenic carbon dioxide, resulting in ocean acidification and changes to carbonate chemistry that are unprecedented in 65 million years at least (*high confidence*). Risks have been identified for the survival, calcification, growth, development, and abundance of a broad range of taxonomic groups (i.e. from algae to fish) with substantial evidence of predictable trait-based sensitivities. Multiple lines of evidence reveal that ocean warming and acidification (corresponding to global warming of 1.5°C of global warming) is expected to impact a wide range of marine organisms, ecosystems, as well as sectors such as aquaculture and fisheries (*high confidence*) {3.3.10, 3.4.4}.

There are larger risks at 1.5°C than today for many regions and systems, with adaptation being required now and up to 1.5°C. There are, however, greater risks and effort needed for adaptation to 2°C *(high confidence)* {3.4, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this Chapter}.

Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (*high confidence*). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, *medium confidence*). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.

Climate change risks for natural and human systems

Terrestrial and Wetland Ecosystems

Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (*medium confidence*). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (*high confidence*). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (*high confidence*), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.

Constraining global warming to 1.5°C rather than 2°C and higher has strong benefits for terrestrial and wetland ecosystems and for the preservation of their services to humans (*high confidence*). Risks for natural and managed ecosystems are higher on drylands compared to humid lands. The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (*high confidence*). Above 1.5°C, an expansion of desert and arid vegetation would occur in the Mediterranean biome (*medium confidence*), causing changes unparalleled in the last 10,000 years (*medium confidence*) {3.3.2.2, 3.4.3.5, 3.4.6.1., 3.5.5.10, Box 4.2}.

Many impacts are projected to be larger at higher latitudes due to mean and cold-season warming rates above the global average (*medium confidence*). High-latitude tundra and boreal forest are particularly at risk, and woody shrubs are already encroaching into tundra (*high confidence*). Further warming is projected to cause greater effects in a 2°C world than a 1.5°C world, for example, constraining warming to 1.5°C would prevent the melting of an estimated permafrost area of 2 million km^2 over centuries compared to 2°C (*high confidence*) {3.3.2, 3.4.3, 3.4.4}.

Ocean ecosystems

Ocean ecosystems are experiencing large-scale changes, with critical thresholds expected to be reached at 1.5ºC and above (*high confidence*). In the transition to 1.5°C, changes to water temperatures will drive some species (e.g. plankton, fish) to relocate to higher latitudes and for novel ecosystems to appear *(high confidence)*. Other ecosystems (e.g. kelp forests, coral reefs) are relatively less able to move, however, and will experience high rates of mortality and loss (*very high confidence*). For example, multiple lines of evidence indicate that the majority of warmer water coral reefs that exist today (70-90%) will largely disappear when global warming exceeds 1.5°C (*very high confidence*) {3.4.4, Box 3.4}.

Current ecosystem services from the ocean will be reduced at 1.5ºC, with losses being greater at 2ºC (*high confidence*). The risks of declining ocean productivity, shifts of species to higher latitudes, damage to ecosystems (e.g. coral reefs, as well as from mangroves, seagrass and other wetland ecosystems), loss of fisheries productivity (at low latitudes), and changing ocean chemistry (e.g., acidification, hypoxia, dead zones), however, are projected to be substantially lower when global warming is limited to 1.5°C (*high confidence*) {3.4.4, Box 3.4}.

Water Resources

The projected frequency and magnitude of floods and droughts in some regions are smaller under a 1.5°C versus 2°C of warming (*medium confidence*). Human exposure to increased flooding is projected to be substantially lower at 1.5°C as compared to 2°C of global warming, although projected changes create regionally differentiated risks (*medium confidence*). The differences in the risks among regions are strongly influenced by local socio-economic conditions (*medium confidence*) {3.3.4, 3.3.5, 3.4.2}.

Risks to water scarcity are greater at 2°C than at 1.5°C of global warming in some regions (*medium confidence*). Limiting global warming to 1.5°C would approximately halve the fraction of world population expected to suffer water scarcity as compared to 2°C, although there is considerable variability between regions (*medium confidence*). Socioeconomic drivers, however, are expected to have a greater influence on these risks than the changes in climate (*medium confidence*) {3.3.5, 3.4.2, Box 3.5}.

Land Use, Food Security and Food Production Systems

Global warming of 1.5°C (as opposed to 2ºC) is projected to reduce climate induced impacts on crop yield and nutritional content in some regions (*high confidence*). Affected areas include Sub-Saharan Africa (West Africa, Southern Africa), South-East Asia, and Central and South America. A loss of 7-10% of rangeland livestock globally is projected for approximately 2°C of warming with considerable economic consequences for many communities and regions {3.6, 3.4.6, Box 3.1, Cross-Chapter Box 6 in this Chapter}.

Risks of food shortages are lower in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon at 1.5ºC of global warming when compared to 2°C (*medium confidence*). This suggests a transition from medium to high risk of regionally differentiated impacts between 1.5 and 2°C for food security (*medium confidence*). International food trade is *likely* to be a potential adaptation response for alleviating hunger in low- and middle-income countries {Cross-Chapter Box 6 in this Chapter}.

Fisheries and aquaculture are important to global food security but are already facing increasing risks from ocean warming and acidification (*medium confidence*), which will increase at 1.5°C global warming. Risks are increasing for marine aquaculture and many fisheries at warming and acidification at 1.5°C (e.g., many bivalves such as oysters, and fin fish; *medium confidence*), especially at low latitudes (*medium confidence*). Small-scale fisheries in tropical regions, which are very dependent on habitat provided by coastal ecosystems such as coral reefs, mangroves, seagrass and kelp forests, are at a high risk at 1.5°C due to loss of habitat (*medium confidence*). Risks of impacts and decreasing food security become greater as warming and acidification increase, with substantial losses likely for coastal livelihoods and industries (e.g. fisheries, aquaculture) as temperatures increase beyond 1.5°C (*medium to high confidence*). {3.4.4, 3.4.5, 3.4.6, Box 3.1, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this Chapter}

Land use and land-use change emerge as a critical feature of virtually all mitigation pathways that seek to limit global warming to 1.5ºC (*robust evidence, high agreement*). Most least-cost mitigation pathways to limit peak or end-of-century warming to 1.5°C make use of Carbon Dioxide Removal (CDR), predominantly employing significant levels of Bioenergy with Carbon Capture and Storage (BECCS) and/or Afforestation and Reforestation (AR) in their portfolio of mitigation measures (*robust evidence, high agreement*) {Cross-Chapter Box 7 in this Chapter}.

Large-scale, deployment of BECCS and/or AR would have a far-reaching land and water footprint (*medium evidence, high agreement*). Whether this footprint results in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, measures to limit agricultural expansion so as to protect natural ecosystems, and the potential to increase agricultural productivity (*high agreement, medium evidence*). In addition, BECCS and/or AR would also have substantial direct effects on regional climate through biophysical feedbacks, which are generally not included in Integrated Assessments Models (*high confidence*). {Cross-Chapter Boxes 7 and 8 in this Chapter, Section 3.6.2}

The impacts of large-scale CDR deployment can be greatly reduced if a wider portfolio of CDR options is deployed, a holistic policy for sustainable land management is adopted and if increased mitigation effort strongly limits demand for land, energy and material resources, including through lifestyle and dietary change (*medium agreement, medium evidence*). In particular, reforestation may be associated with significant co-benefits if implemented so as to restore natural ecosystems *(high confidence)* {Cross-Chapter Box 7 in this Chapter}

Human Systems: Human Health, Well-Being, Cities, and Poverty

Any increase in global warming (e.g., +0.5ºC) will affect human health (*high confidence*). Risks will be lower at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*), particularly in urban areas because of urban heat islands (*high confidence*). Risks also will be greater for ozone-related mortality if the emissions needed for the formation of ozone remain the same (*high confidence*), and for undernutrition (*medium confidence*). Risks are projected to change for some vector-borne diseases such as malaria and dengue fever (*high confidence*), with positive or negative trends depending on the disease, region, and extent of change (*high confidence*). Incorporating estimates of adaptation into projections reduces the magnitude of risks (*high confidence*) {3.4.7, 3.4.7.1}.

Global warming of 2°C is expected to pose greater risks to urban areas than global warming of 1.5°C (*medium confidence*). The extent of risk depends on human vulnerability and the effectiveness of adaptation for regions (coastal and non-coastal), informal settlements, and infrastructure sectors (energy, water, and transport) (*high confidence*) {3.4.5, 3.4.8}.

Poverty and disadvantage have increased with recent warming (about 1ºC) and are expected to increase in many populations as average global temperatures increase from 1ºC to 1.5°C and beyond (*medium confidence*). Outmigration in agricultural-dependent communities is positively and statistically significantly associated with global temperature (*medium confidence*). Our understanding of the linkages of 1.5ºC and 2ºC on human migration are limited and represent an important knowledge gap {3.4.10, 3.4.11, 5.2.2, Table 3.5}.

Key Economic Sectors and Services

Globally, the projected impacts on economic growth in a 1.5°C warmer world are larger than those of the present-day (about 1°C), with the largest impacts expected in the tropics and the Southern Hemisphere subtropics (*limited evidence, low confidence*). At 2°C substantially lower economic growth is projected for many developed and developing countries *(limited evidence, medium confidence)*, with the potential to also limit economic damages at 1.5°C of global warming. {3.5.2, 3.5.3}.

The largest reductions in growth at 2°C compared to 1.5 °C of warming are projected for low- and middle-income countries and regions (the African continent, southeast Asia, India, Brazil and Mexico) (*limited evidence, medium confidence*) {3.5}.

Global warming has affected tourism and increased risks are projected for specific geographic regions and the seasonality of sun, beach, and snow sports tourism under warming of 1.5ºC (*very high confidence*). Risks will be lower for tourism markets that are less climate sensitive, such as non-environmental (e.g., gaming) or large hotel-based activities (*high confidence*) {3.4.9.1}. Risks for coastal tourism, particularly in sub-tropical and tropical regions, will increase with temperature-related degradation (e.g. heat extremes, storms) or loss of beach and coral reef assets (*high confidence*) {3.4.9.1, 3.4.4.12; 3.3.6, Box 3.4}.

Small islands, and coastal and low-lying areas

Small islands are projected to experience multiple inter-related risks at 1.5°C that will increase with warming of 2ºC and higher (*high confidence*). Climate hazards at 1.5°C are lower compared to 2°C (*high confidence*). Long term risks of coastal flooding and impacts on population, infrastructure and assets (*high confidence*), freshwater stress (*medium confidence*), and risks across marine ecosystems (*high confidence*), and critical sectors (*medium confidence)* increase at 1.5°C as compared to present and further increase at 2°C, limiting adaptation opportunities and increasing loss and damage (*medium confidence*). Migration in small islands (internally and internationally) occurs due to multiple causes and for multiple purposes, mostly for better livelihood opportunities (*high confidence*) and increasingly due to sea level rise (*medium confidence*). {3.3.2.2, 3.3.6-9, 3.4.3.2, 3.4.4.2, 3.4.4.5, 3.4.4.12, 3.4.5.3, 3.4.7.1, 3.4.9.1, 3.5.4.9, Box 3.4, Box 3.5}.

Impacts associated with sea level rise and changes to the salinity of coastal groundwater, increased flooding and damage to infrastructure, are critically important in sensitive environments such as small islands, low lying coasts and deltas at global warming of 1.5ºC and 2ºC (*high confidence*). Localised subsidence and changes to river discharge can potentially exacerbate these effects {3.4.5.4}. Adaptation is happening today (*high confidence*) and remains important over multi-centennial timescales {3.4.5.3, 3.4.5.7, Box 3.5, 5.4.5.4}.

Existing and restored natural coastal ecosystems may be effective in reducing the adverse impacts of rising sea levels and intensifying storms by protecting coastal and deltaic regions. Natural sedimentation rates are expected to be able to offset the effect of rising sea levels given the slower rates of sea-level rise associated with 1.5°C of warming (*medium confidence*). Other feedbacks, such as landward migration of wetlands and the adaptation of infrastructure, remain important (*medium confidence*) {3.4.4.12, 3.4.5.4, 3.4.5.7}

Increased reasons for concern

There are multiple lines of evidence that there has been a substantial increase since AR5 in the levels of risk associated with four of the five Reasons for Concern (RFCs) for global warming levels of up to 2°C (*high confidence*). Constraining warming to 1.5ºC rather than 2ºC avoids risk reaching a 'very high' level in RFC1 (Unique and Threatened Systems) (*high confidence*), and avoids risk reaching a 'high' level in RFC3 (Distribution of Impacts) (*high confidence*) and RFC4 (Global Aggregate Impacts) (*medium confidence*). It also reduces risks associated with RFC2 (Extreme Weather Events) and RFC5 (Large scale singular events) (*high confidence*) {3.5.2}.

In "Unique and Threatened Systems" (RFC1) the transition from high to very high risk is located between 1.5ºC and 2ºC global warming as opposed to at 2.6ºC global warming in AR5, owing to new and multiple lines of evidence for changing risks for coral reefs, the Arctic, and biodiversity in general (*high confidence*) {3.5}.

1. **In "Extreme Weather Events" (RFC2) the transition from moderate to high risk is located between 1.0ºC and 1.5ºC global warming,** which is very similar to the AR5 assessment but there is greater confidence in the assessment (*medium confidence*). The impact literature contains little

information about the potential for human society to adapt to extreme weather events and hence it has not been possible to locate the transition from 'high' (red) to 'very high' risk within the context of assessing impacts at 1.5°C versus 2°C global warming. There is thus *low confidence* in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report {3.5}.

2. **In "Distribution of impacts" (RFC3) a transition from moderate to high risk is now located between 1.5ºC and 2ºC global warming as compared with between 1.6**ºC **and 2.6**ºC **global warming in AR5**, due to new evidence about regionally differentiated risks to food security, water resources, drought, heat exposure, and coastal submergence *(high confidence)* {3.5}.

3. **In "Global aggregate impacts" (RFC4) a transition from moderate to high levels of risk now occurs between 1.5ºC and 2.5ºC global warming** as opposed to at 3ºC warming in AR5, owing to new evidence about global aggregate economic impacts and risks to the earth's biodiversity *(medium confidence)* {3.5}.

4. **In "Large scale singular events" (RFC5), moderate risk is located at 1ºC global warming and high risks are located at 2.5ºC global warming**, as opposed to 1.9ºC (moderate) and 4ºC global warming (high) risk in AR5 because of new observations and models of the West Antarctic ice sheet (*medium confidence*) {3.3.9, 3.5.2, 3.6.3}

3.1 About the chapter

Chapter 3 uses relevant definitions of a potential 1.5°C warmer world from Chapters 1 and 2 and builds directly on their assessment of gradual versus overshoot scenarios. It interacts with information presented in Chapter 2 via the provision of specific details relating to the mitigation pathways (e.g., land use changes) and their implications for impacts. Information for the assessment and implementation of adaptation options in Chapter 4, and the context for considering the interactions of climate change with sustainable development in Chapter 5 for the assessment of impacts on sustainability, poverty and inequalities at the level of sub-regions to households, are provided by Chapter 3.

This chapter is necessarily transdisciplinary in its coverage of the climate system, natural and managed ecosystems, and human systems and responses, due to the integrated nature of the natural and human experience. While climate change is acknowledged as a centrally important driver, it is not the only driver of risks to human and natural systems, and in many cases, it is the interaction between these two broad categories of risk that is important (Chapter 1).

The flow of the chapter, linkages between sections, a list of chapter and cross chapter boxes, and a content guide for reading according to focus or interest are given in Figure 3.1. Key definitions used in the chapter are collected in the Glossary. Confidence language is used throughout this chapter and likelihood statements (e.g. *likely*, *very likely*) are provided when there is *high* confidence in the assessment.

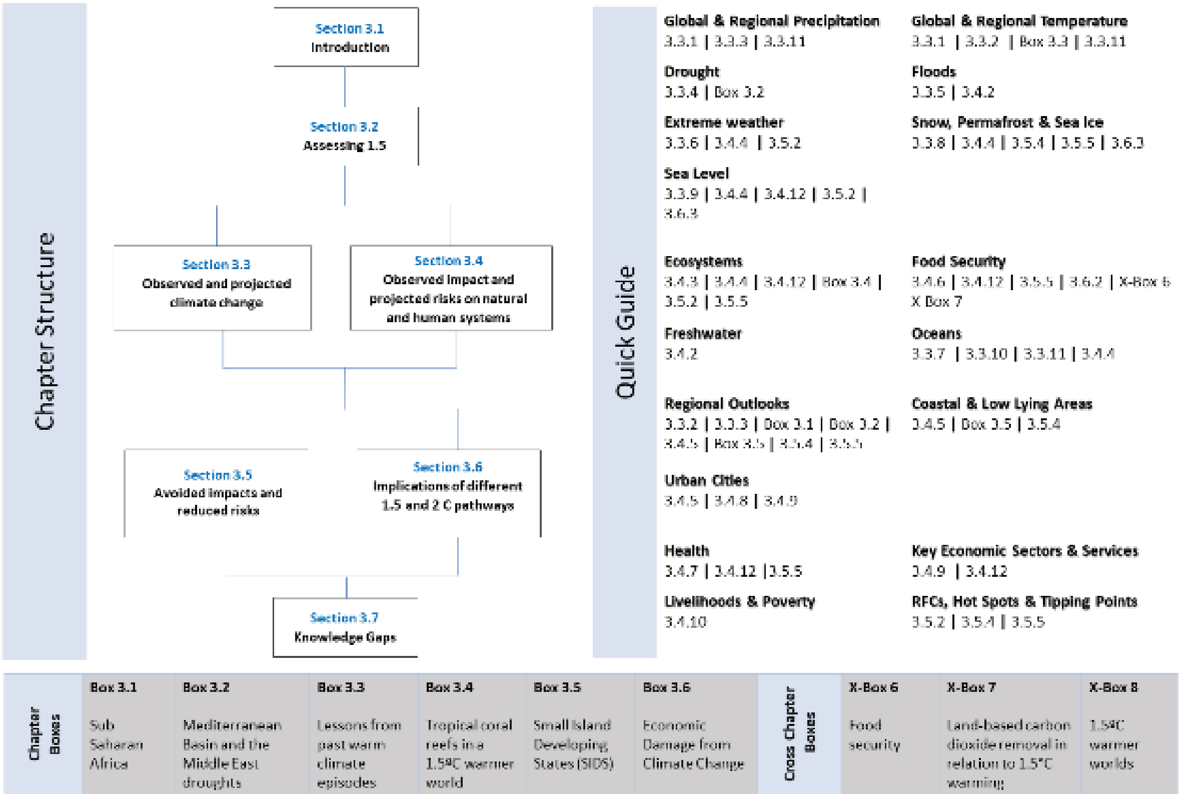


Figure 3.1: Chapter 3 structure and quick guide

The underlying literature assessed in Chapter 3 is broad, including a large number of recent publications specific to assessments for 1.5°C warming. The chapter also utilizes information covered in prior IPCC special reports, for example Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, IPCC, 2012), and many chapters which assess impacts on natural and managed ecosystems and humans and adaptation options from the IPCC WGII Fifth Assessment Report (AR5) (IPCC, 2014b). For this reason, the chapter provides information based on a broad range of assessment methods. Details about the approaches used are presented in Section 3.2.

Section 3.3 gives a general overview of recent literature on observed climate change impacts as the context for projected future risks. With a few exceptions, the focus is on analyses of *transient responses* at 1.5°C and 2°C, with simulations of *short-term stabilization scenarios* (Section 3.2) also assessed in some cases. In general, *long-term equilibrium stabilization responses* could not be assessed due to lack of data availability. A detailed analysis of detection and attribution is not provided. Furthermore, possible interventions in the climate system through radiation modification measures which are not tied to reductions of greenhouse gas emissions or concentrations are not assessed in this chapter.

Understanding the observed impacts and projected risks of climate change forms a crucial element in understanding how the world is likely to change under global warming of 1.5°C above the preindustrial period (with reference to 2ºC). Section 3.4 explores the new literature and updates the assessment of impacts and projected risks into the future for a large number of natural and human systems. By also exploring adaptation opportunities (where the literature allows), the section prepares the ground for later discussions in subsequent chapters about opportunities to tackle both mitigation and adaptation. The section is mostly globally focussed because of limited research on regional risks and adaptation options at 1.5ºC and 2ºC. For example, on the risks of warming of 1.5°C and 2°C in urban areas, and climate-sensitive health outcomes, such as climate related disease, medical impacts of poor air quality, or mental health, were not considered because of the lack of projections of how risks might change in 1.5ºC and 2°C worlds. In addition, the complex interactions of climate change with drivers of poverty and livelihoods meant it was not possible to detect and attribute recent changes to climate change, even with increasing documentation of climate-related impacts on places where indigenous peoples live and where subsistence-oriented communities are to be found, because of limited projections of the risks associated with warming of 1.5ºC and 2ºC.

To explore avoided impacts and reduced risks at 1.5ºC compared with 2ºC, the chapter adopts the AR5 'Reasons for Concern' aggregated projected risk framework (Section 3.5). Updates in terms of the aggregation of risk are informed by the most recent literature and the assessments offered in Sections 3.3 and 3.4 with focus on the avoided impacts at 1.5°C as compared to 2°C. Economic benefits to be obtained (Section 3.5.3), climate change 'hot spots' that can be avoided or reduced (Section 3.5.4 as guided by the assessments of Sections 3.3, 3.4 and 3.5), and tipping points that can be avoided (Section 3.5.5) at 1.5ºC compared to higher degrees of global warming, are all examined. These latter assessments are, however, constrained to regional analysis, and the section does not include an assessment of loss and damages.

Section 3.6 provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C global warming including some overshoot above 1.5°C global warming during the 21st century. Non-CO_2 implications and projected risks of mitigation pathways, such as changes to land use and atmospheric compounds are presented and explored. Finally, implications for sea ice, sea level and permafrost beyond the end of the century are assessed.

The exhaustive assessment of 1.5°C specific literature presented across all the sections in Chapter 3 highlighted knowledge gaps resulting from the heterogeneous information across systems, regions and sectors. Some of these gaps are listed in Section 3.7.

3.2 How are risks at 1.5°C and higher levels of global warming assessed in this chapter?

The methods that are applied for assessing observed and projected changes in climate and weather are presented in Section 3.2.1 while those used for assessing the observed impacts and projected risks to natural and managed systems, and human settlements, are described in Section 3.2.2. Given that changes in climate associated with 1.5°C of global warming were not the focus of past IPCC reports, dedicated approaches based on recent literature and which are specific to the present report, are also described. Background on specific methodological aspects (climate model simulations available for assessments at 1.5°C global warming, attribution of observed changes in climate and their relevance for assessing projected changes at 1.5°C and 2°C global warming, and the propagation of uncertainties from climate forcing to impacts on the ecosystems) are provided in the Annex 3-1.

3.2.1 How are changes in climate and weather at 1.5°C versus higher levels of warming assessed?

Evidence for the assessment of changes to climate at 1.5°C versus 2°C can draw both from observations and model projections. Global Mean Surface Temperature (GMST) anomalies were about +0.87°C (±0.10°C *likely* range) above pre-industrial industrial (1850-1900) values in the 2006-2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (Chapter 1). Human-induced global warming reached approximately 1ºC (±0.2°C *likely* range) in 2017 (Chapter 1). While some of the observed trends may be due to internal climate variability, methods of detection and attribution can be applied to assess which part of the observed changes may be attributed to anthropogenic forcing (Bindoff et al., 2013b). Hence, evidence from attribution studies can be used to assess changes in the climate system that are already detectable at lower levels of global warming and would thus continue to change for a further increase of 0.5°C or 1°C in global warming (see Annex 3.1 S3-2 and Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.11). A recent study also investigated significant changes in extremes for a 0.5°C difference in global warming based on the historical record (Schleussner et al., 2017).

Climate model simulations are necessary for the investigation of the response of the climate system to various forcings, in particular for forcings associated with higher levels of greenhouse gas concentrations. Model simulations include experiments with global and regional climate models, as well as impact models (driven with output from climate models) to evaluate the risk related to climate change for natural and human systems (Annex 3.1, S3.2). Climate model simulations were generally used in the context of particular 'climate scenarios' in previous IPCC reports (e.g., IPCC, 2007, 2013). This means that emission scenarios (IPCC, 2000) were used to drive climate models, providing different projections for given emissions pathways. The results were consequently used in a 'storyline' framework, which presents the development of climate in the course of the 21st century and beyond, if a given emission pathway was to be followed. Results were assessed for different time slices within the model projections, for example for 2016-2035 ('near term', which is slightly below a 1.5°C global warming in most scenarios, Kirtman et al., 2013), 2046-65 (mid 21st century, Collins et al., 2013), and 2081-2100 (end of 21st century, Collins et al., 2013). Given that this report focuses on climate change for a given mean global temperature response (1.5°C or 2°C), methods of analysis had to be developed and/or adapted from previous studies in order to provide assessments for the specific purposes here.

A major challenge in assessing climate change under 1.5°C (or 2°C and higher-level) global warming pertains to the **definition of a '1.5°C or 2°C climate projection'** (see also Cross-Chapter Box 8 in this Chapter). Resolving this challenge includes the following considerations:

A. The need for distinguishing between (a) **transient climate responses** (i.e. those that 'pass through' 1.5°C or 2°C global warming), (b) **short-term stabilization responses** (i.e. late 21st-century scenarios that result in stabilization at a mean global warming of 1.5°C or 2°C by 2100), and (c) **long-term equilibrium stabilization responses** (i.e. once climate equilibrium at 1.5°C or 2°C is reached, after several millennia). These responses can be very different in terms of climate variables and the inertia associated with a given climate forcing. A striking example is Sea Level Rise (SLR). In this case, projected increases within the 21st century are minimally dependent on the considered scenario yet stabilize at very different levels for a long-term warming of 1.5°C versus 2°C (Section 3.3.9).

B. That '1.5°C or 2°C emissions scenarios' presented in Chapter 2 are targeted to hold warming below 1.5°C or 2°C with a certain probability (generally 2/3) over the course, or end, of the 21st century.

These scenarios should be seen as operationalisations of 1.5°C or 2°C worlds. However, when these emission scenarios are used to drive climate models, some of the resulting simulations lead to warming above these respective thresholds (typically with a probability of 1/3, see Chapter 2 and Cross-Chapter Box 8 in this Chapter). This is due both to discrepancies between models and internal climate variability. For this reason, the climate outcome for any of these scenarios, even those excluding an overshoot (see next point, C.), include some probability of reaching a global climate warming higher than 1.5°C or 2°C. Hence, a comprehensive assessment of climate risks associated with '1.5°C or 2°C climate scenarios' needs to include consideration of higher levels of warming (e.g. up to 2.5°C -3°C, see Chapter 2 and Cross-Chapter Box 8 in this Chapter).

C. Most of the '1.5°C scenarios', and some of the '2°C emissions scenarios' of Chapter 2, include a temperature overshoot during the course of the 21st century. This means that median temperature projections under these scenarios exceed the target warming levels over the course of the century (typically up to 0.5°C-1°C higher than the respective target levels at most), before warming returns to below 1.5°C or 2°C achieved by 2100. During the overshoot phase, impacts would therefore correspond to higher transient temperature levels than 1.5°C or 2°C. For this reason, impacts for transient responses at these higher levels are also partly addressed in Cross-Chapter Box 8 in this Chapter on 1.5°C warmer worlds, and some analyses for changes in extremes are also displayed for higher levels of warming in Section 3.3 (Figures 3.5, 3.6, 3.9, 3.10, 3.12, 3.13). Most importantly, different overshoot scenarios may have very distinct impacts depending on (a) the peak temperature of the overshoot, (b) the length of the overshoot period, and (c) the associated rate of change in global temperature over the time period of the overshoot. While some of these issues are briefly addressed in Sections 3.3 and 3.6, and the Cross-Chapter Box 8 (in this Chapter), the definition and questions surrounding overshoot will need to be addressed more comprehensively in the IPCC AR6 report.

D. The meaning of '1.5°C or 2°C' global warming climate was not defined prior to this report, although it is defined as relative to the climate associated with the Pre-Industrial Period. This requires an agreement on the exact reference time period (for 0°C warming) and the time frame over which the global warming is assessed (e.g. typically a climatic time period, such as one that is 20 or 30 years in length). As discussed in Chapter 1, a 1.5°C climate is one in which temperature differences averaged over a multi-decade timescale are 1.5°C above the pre-industrial reference period. Greater detail is provided in the Cross-Chapter Box 8. Inherent to this is the observation that the mean temperature of a '1.5°C warmer world' can be regionally and temporally much higher (e.g. regional annual temperature extremes can display a warming of up to 4.5°C on average, see Section 3.3 and Cross-Chapter Box 8 in this Chapter).

E. Non-greenhouse gas related interference with mitigation pathways can strongly affect regional climate. For example, biophysical feedbacks from changes in land use and irrigation (e.g. Hirsch et al., 2017; Thiery et al., 2017), or projected changes in short-lived pollutants (e.g. Z. Wang et al., 2017), can have large influences on local temperatures and climate conditions. While these effects are not explicitly integrated into the scenarios developed in Chapter 2, they may affect projected changes in climate for 1.5°C of global warming. These issues are addressed in more detail in Section 3.6.2.2.

The assessment done in the current chapter largely focusses on the analysis of **transient responses in climate at 1.5°C versus 2°C** and higher levels of warming (see point A. above, Section 3.3). It generally uses the Empirical Scaling Relationship approach (ESR, Seneviratne et al., 2018c), also termed 'time sampling' approach (James et al., 2017), which consists of sampling the response at 1.5°C and other levels of global warming from all available global climate model scenarios for the 21st century (e.g., Schleussner et al., 2016b; Seneviratne et al., 2016; Wartenburger et al., 2017). The ESR approach focuses more on the derivation of a continuous relationship, while the term time sampling is more commonly used when comparing a limited number of warming levels (e.g. 1.5°C versus 2°C). A similar approach in the case of Regional Climate Model (RCM) simulations consists of sampling the RCM model output corresponding to the time frame at which the driving General Circulation Model (GCM) reaches the considered temperature level (e.g., as done within the IMPACT2C project (Jacob and Solman, 2017), see description in Vautard et al. (2014)). As an alternative to the ESR or time sampling approach, pattern scaling may be used. Pattern scaling is a statistical approach that describes relationships of specific climate responses as a function of global temperature change. Some assessments of this chapter are also based on this method. The disadvantage of pattern scaling, however, is that the relationship may not perfectly emulate the models' responses at each location and for each global temperature level (James et al., 2017). Expert judgement is a third methodology that can be used to assess probable changes at 1.5°C or 2°C by combining changes that have been attributed for the observed time period (corresponding already to a warming of 1°C or smaller if assessed over a shorter time period) and known projected changes at 3°C or 4°C above the pre-industrial (Annex 3.1 S3-2). In order to compare effects induced by a 0.5°C difference in global warming, it is also possible to use, in a first approximation, the historical record as a proxy in which two periods are compared in cases where they approximate this difference in warming (e.g. such as 1991-2010 and 1960-1979, e.g. Schleussner et al., 2017). Using observations, however, does not allow an accounting for possible non-linear changes that would occur above 1°C or as 1.5°C of global warming is achieved.

In some cases, assessments for **short-term stabilization responses** could also be provided, derived from using a subset of model simulations that reach a given temperature limit by 2100, or were driven with Sea Surface Temperature (SST) consistent with such scenarios. This includes new results from the 'Half a degree additional warming, prognosis and projected impacts' (HAPPI) project (Chapter 1, Section 1.5.2, Mitchell et al., 2017). It should be noted that there is evidence that for some variables (e.g. temperature and precipitation extremes), responses after short-term stabilization (i.e. approximately equivalent to the RCP2.6 scenario) are very similar to the transient response of higher-emission scenarios (Seneviratne et al., 2016, 2018a; Wartenburger et al., 2017; Tebaldi and Knutti, 2018). This is, however, less the case for mean precipitation (e.g., Pendergrass et al., 2015)) for which other aspects of the emissions scenarios appear relevant.

For the assessment of **long-term equilibrium stabilization responses**, this chapter uses results from existing simulations where available (e.g. for sea level rise), although the available data for this type of projections is limited for many variables and scenarios and will need to be addressed in more depth in the IPCC AR6 report.

Annex 3.1 (S3-2) of this chapter includes greater detail of the climate models and associated simulations that were used to support the present assessment, as well as a background on detection and attribution approaches of relevance to assessing changes in climate at 1.5°C global warming.

3.2.2 How are potential impacts on ecosystems assessed at 1.5°C versus higher levels of warming?

Considering that the observed impacts so far are for a lower global warming than 1.5°C (generally up to the 2006-2015 decade, i.e. for a global warming of 0.87°C or less; see above), direct information on the impacts of a global warming of 1.5°C is not yet available. The global distribution of observed impacts shown in the AR5 (Cramer et al., 2014), however, demonstrates that methodologies now exist which are capable of detecting impacts in systems strongly influenced by confounding factors (e.g. urbanization or more generally human pressure) or where climate may play only a secondary role in driving impacts. Attribution of observed impacts to greenhouse gas forcing is more rarely performed, but a recent study (Hansen and Stone, 2016) shows that most of the detected temperature-related impacts that were reported in the AR5 (Cramer et al., 2014) can be attributed to anthropogenic climate change, while the signals for precipitation-induced responses are more ambiguous.

One simple approach for assessing possible impacts on natural and managed systems at 1.5ºC versus 2°C consists of identifying impacts of a global 0.5°C warming in the observational record (e.g., Schleussner et al., 2016b), assuming that the impacts would scale linearly for higher levels of warming (although this may not be appropriate). Another approach is to use conclusions from past climates combined with the modeling of the relationships between climate drivers and natural systems (Box 3.3). A more complex approach relies on laboratory or field experiments (Dove et al., 2013; Bonal et al., 2016) which provide useful information on the causal effect of a few factors (which can be as diverse as climate, greenhouse gases (GHG), management practices, biological and ecological factors) on specific natural systems that may have unusual physical and chemical characteristics (e.g., Fabricius et al., 2011; Allen et al., 2017). The latter can be important in helping to develop and calibrate impact mechanisms and models through empirical experimentation and observation.

Risks for natural and human systems are often assessed with impact models where climate inputs are provided by Representative Concentration Pathway (RCP)-based climate projections. Studies projecting impacts at 1.5°C or 2°C global warming have increased in recent times (see Section 3.4) even if the four RCP scenarios used in the AR5 are not strictly associated to these levels of global warming levels. Several approaches have been used to extract the required climate scenarios, as described in Section 3.2.1. As an example, Schleussner et al. (2016b) applied time sampling (or ESR) approach (described in Section 3.2.1) to estimate the differential effect of 1.5°C and 2°C global warming on water availability and impacts on agriculture using an ensemble of simulations under the RCP8.5 scenario. As a further example using a different approach, Iizumi et al. (2017) derived a 1.5°C scenario from simulations with an crop model using interpolation between the no-change (approximately 2010) conditions and the RCP2.6 scenario (with a global warming of +1.8°C in 2100), and derived the corresponding 2°C scenario from RCP2.6 and RCP4.5 simulations in 2100. The Inter-Sectoral Impact Model Integration and Intercomparison Project Phase 2 (ISIMIP2) (Frieler et al., 2017) extended this approach to a number of sectoral impacts on the terrestrial and marine ecosystems. In most cases, the risks are assessed by impact models coupled offline to climate models after bias correction, which may modify long-term trends (Grillakis et al., 2017).

Assessment of local impacts of climate change necessarily involves a change in scale (i.e from the global scale to that of natural or human systems) (Frieler et al., 2017; Reyer et al., 2017d; Jacob et al., 2018). An appropriate method of downscaling (Annex 3.1 S3-2) is crucially important in translating perspectives on 1.5°C and 2°C to scales and impacts relevant to humans and ecosystems. A major challenge that is associated with this requirement is to reproduce correctly the variance of local to regional changes, as well as the frequency and amplitude of the extreme events (Vautard et al., 2014). In addition, maintaining physical consistency between downscaled variables is also important, but challenging (Frost et al., 2011).

Another major challenge relates to the propagation of the uncertainties at each step of the methodology, from the global forcings to the global climate, and regional climate to the impacts at the ecosystem level, taking into account local disturbances and local policy effects. The risks for natural and human systems are the result of intricate global and local drivers, which makes quantitative uncertainty analysis difficult. Such analyses are partly done using multi-model approaches, such as multi-climate and multi-impact models (Warszawski et al., 2013, 2014; Frieler et al., 2017). In some cases, the greater proportion of the uncertainty (e.g., crop projections) is due to variation among crop models rather than that of the downscaled climate models being used (Asseng et al., 2013). The study of the error propagation is an important issue for coupled models. Dealing correctly with the uncertainties in a robust probabilistic model is particularly important when considering the potential for relatively small changes to affect the already small signal associated with 0.5°C (Annex 3.1 S3-2). The computation of the impact per unit of climatic change either based on models or data is a simple way to present the probabilistic ecosystem response taking into account the various sources of uncertainties (Fronzek et al., 2011).

In summary, in order to assess risks at 1.5°C and higher levels of global warming, several considerations need to be taken into account. Projected climates under 1.5°C of global warming can be different depending on the temporal aspects and pathways of emissions. Considerations include whether global temperature is a) temporarily at this level (i.e. is a transient phase on its way to higher levels of warming), b) arrives at 1.5°C after stabilization of greenhouse gas concentrations with or without overshoot, or c) is at this level as part of long-term climate equilibrium (after several millennia). Assessments of impacts of 1.5°C warming are generally based on climate simulations for these different possible pathways. More data and analyses are available for transient impacts (a). There are fewer data for dedicated climate model simulations that are able to assess pathways consistent with (b). There are very limited data available for the assessment of changes at climate equilibrium (c). In some cases, inferences regarding the impacts of further warming of 0.5°C above today (i.e. 1.5°C global warming) can also be drawn from observations of similar sized changes (0.5°C) that have occurred in the past (e.g. last 50 years). However, impacts can only be partly inferred from these types of observations given the strong possibility of non-linear changes, as well as lag effects for some climate variables (e.g. sea level rise, snow and ice melt). For the impact models, three problems are noted about the coupling procedure: (i) the bias correction of the climate model which may modify the simulated response of the ecosystem, (ii) the necessity to downscale the climate model outputs to reach a pertinent scale for the ecosystem without losing the physical consistency of the downscaled climate fields, and (iii) the necessity to develop an integrated study of the uncertainties.

3.3 Global and regional climate changes and associated hazards

This section provides the assessment of changes in climate at 1.5°C global warming relative to higher global mean temperatures. Section 3.3.1 provides a brief overview of changes to global climate. Sections 3.3.2-3.3.11 provide assessments for specific aspects of the climate system, including regional assessments for temperature (Section 3.3.2) and precipitation (Section 3.3.3) means and extremes. Analyses of regional changes are based on the set of regions displayed in Figure 3.2. A synthesis of the main conclusions of this section is provided in Section 3.3.11. The section builds upon assessments from the IPCC AR5 WG1 report (Bindoff et al., 2013a; Christensen et al., 2013; Collins et al., 2013; Hartmann et al., 2013; IPCC, 2013) and Chapter 3 of the IPCC Special Report on Managing the Risks of Extreme Events and disasters to Advance Climate Change Adaptation (SREX)(Seneviratne et al., 2012), as well as a substantial body of new literature related to projections of climate at 1.5°C and 2°C of warming above the pre-industrial period (e.g., Vautard et al., 2014; Fischer and Knutti, 2015; Schleussner et al., 2016b; Seneviratne et al., 2016, 2018c; Déqué et al., 2017; Maule et al., 2017; Mitchell et al., 2017; Wartenburger et al., 2017; Zaman et al., 2017; Betts et al., 2018; Jacob et al., 2018; Kharin et al., 2018; Mitchell et al., 2018; Wehner et al., 2018). The main assessment methods are as already detailed in Section 3.2.

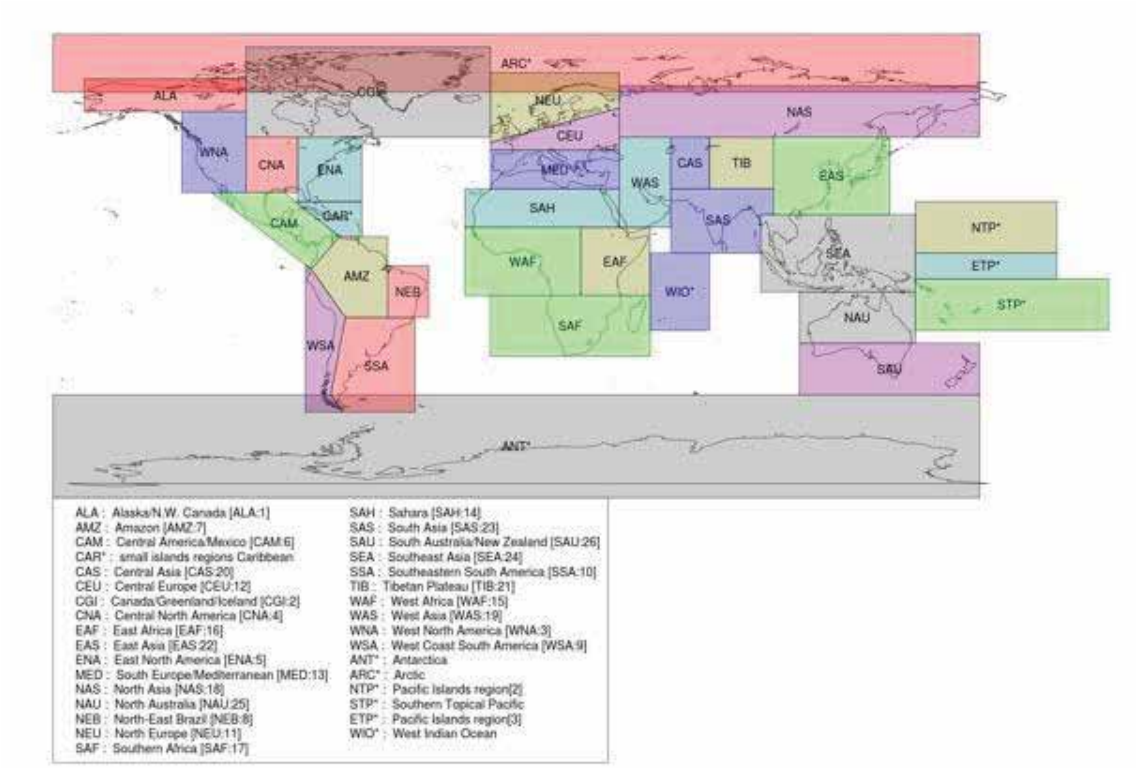


Figure 3.2: Regions used for regional analyses provided in Section 3.3. The choice of regions is based on the IPCC Fifth Assessment Report (AR5, Chapter 14, Christensen et al., 2013) and Annex 1: Atlas) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, Chapter 3, Seneviratne et al., 2012), including seven additional regions (Arctic, Antarctic and islands) compared to the IPCC SREX report (indicated with asterisks). Analyses for regions with asterisks are provided in the Annex (Annex 3.1 S3-3).

3.3.1 Global changes in climate

There is *high confidence* that the Global Mean Surface Temperature (GMST) warming has reached 0.87°C (±0.10°C *likely* range) above pre-industrial in the 2006-2015 decade (Chapter 1). The AR5 assessed that the globally averaged temperature (combined over land and ocean) displayed a warming of about 0.85°C [0.65°C to 1.06°C] for the period 1880-2012, with a large fraction of the detected global warming being attributed to anthropogenic forcing (Bindoff et al., 2013a; Hartmann et al., 2013; Stocker et al., 2013). While new evidence has highlighted that sampling biases and the choice of approaches to estimate GMST (e.g., using water versus air temperature over oceans; model simulations versus observations-based estimates) can affect estimates of GMST warming (Richardson et al., 2016) (see also Annex 3.1 S3.3), the present assessment is consistent with that of the AR5 regarding a detectable and dominant effect of anthropogenic forcing on observed trends in global temperature (e.g., also confirmed in Ribes et al., 2017). As highlighted in Chapter 1, human-induced warming reached approximately 1°C (±0.2°C *likely* range) in 2017. More background on recent observed trends in global climate is provided in the Annex 3-3.

A global warming of 1.5°C implies warmer mean temperatures compared to pre-industrial times in almost all locations on both land and oceans (*high confidence*) (Figure 3.3). In addition, differences resulting from 1.5°C and 2°C global warming are detectable in mean temperatures in almost all locations on both land and ocean (*high confidence*). The land-sea contrast in temperature warming is important and implies particularly large changes in temperature over land, with larger mean warming than 1.5°C in most land regions (*high confidence*; see Section 3.3.2 for more details). The highest warming of the mean temperature is found in the northern high latitudes (*high confidence*; Figure 3.3, see Section 3.3.2 for more details). Projections for precipitation are more uncertain but highlight significant increases in mean precipitation in the Northern Hemisphere high latitudes at 2°C versus 1.5°C global warming (*medium confidence*) (Figure 3.3). For droughts, changes in evapotranspiration and precipitation timing are also relevant (see Section 3.3.4). Figure 3.4 displays changes in temperature extremes (the hottest day of the year, TXx, and the coldest day of the year TNn) and heavy precipitation (the annual maximum 5-day precipitation, Rx5day). These analyses reveal distinct patterns of changes, with highest changes in TXx in mid-latitude land, and highest changes in TNn in high latitudes (both land and oceans). Differences at 1.5°C versus 2°C are significant across the globe. Changes in heavy precipitation are less robust at the grid-cell scale, but display increases over most land areas.

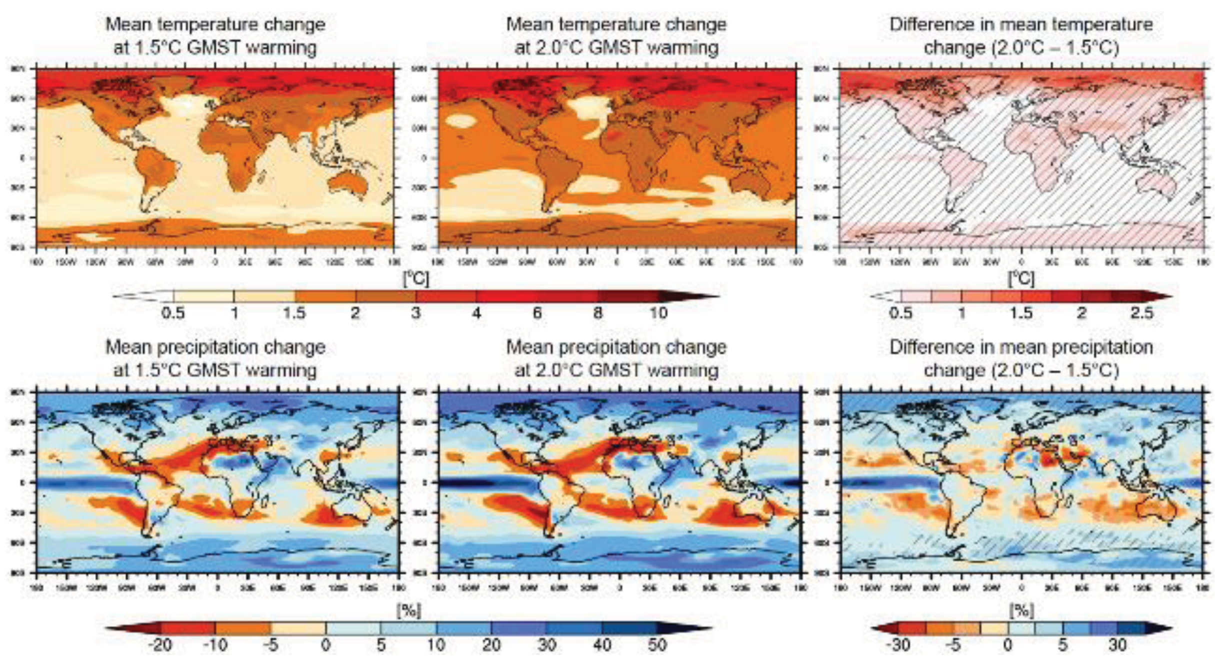


Figure 3.3: Projected mean temperature (top) and mean precipitation changes (bottom) at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Assessed from transient response over 20-year time period at given warming, based on Representative Concentration Pathway (RCP)8.5 Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations (adapted from Seneviratne et al., 2016, and Wartenburger et al., 2017, see Annex 3.1 S3-3 for more details). Note

that the responses at 1.5°C Global Mean Surface Temperature (GMST) warming are similar for RCP2.6 simulations (see Annex 3.1 S3-3).

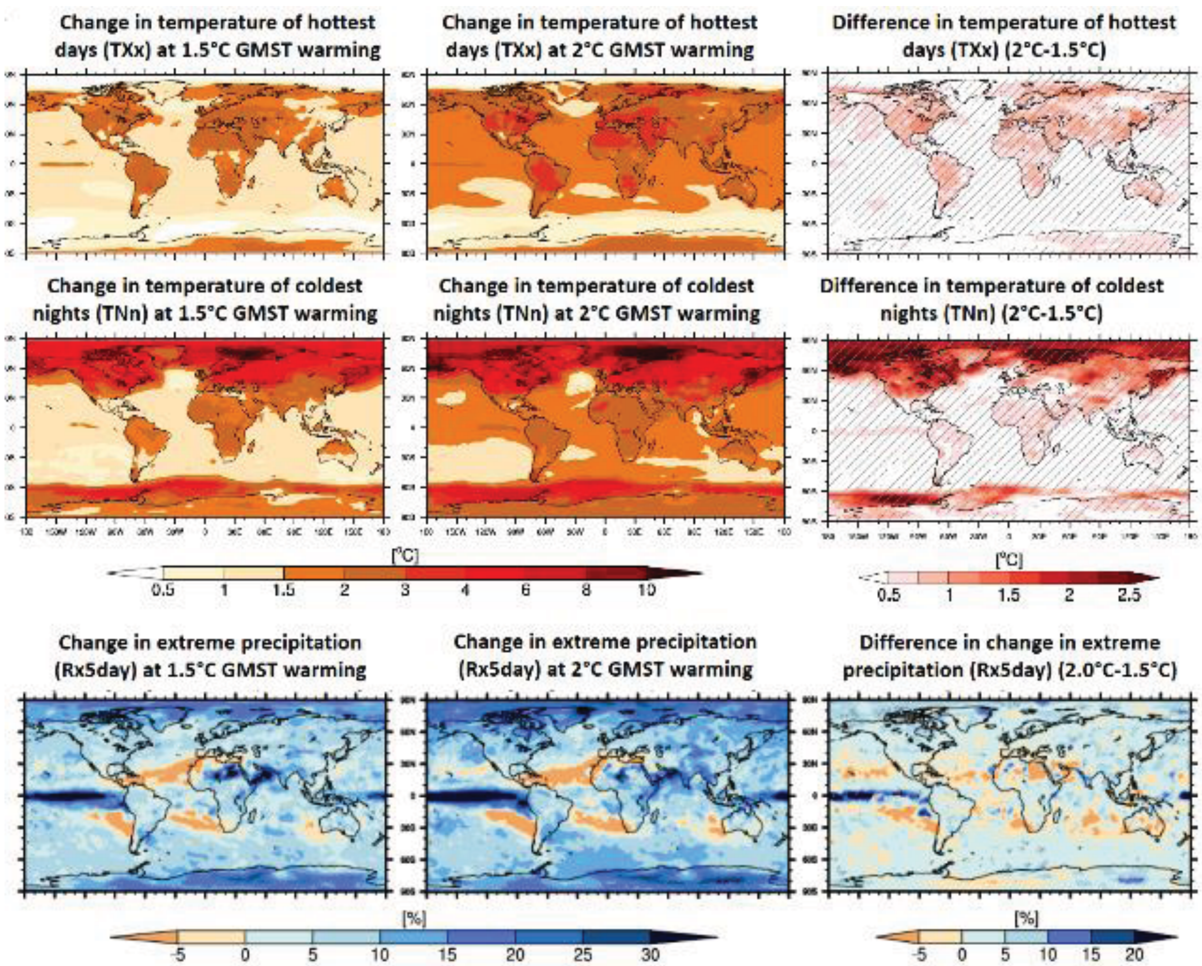


Figure 3.4: Projected change in extreme at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change): temperature of annual hottest day, TXx (top), and annual coldest day, TNn, (middle), and annual maximum 5-day precipitation, Rx5day (bottom). Same underlying methodology and data basis as Figure 3.3 (see Annex 3.1 S3-3 for more details). Note that the responses at 1.5°C Global Mean Surface Temperature (GMST) warming are similar for Representative Concentration Pathway (RCP)2.6 simulations (see Annex 3.1 S3-3).

These projected changes at 1.5°C and 2°C global warming are consistent with the attribution of global observed historical trends in temperature and precipitation means and extremes (Bindoff et al., 2013a) as well as with some observed changes for a recent global warming of 0.5°C (Schleussner et al., 2017), as also addressed in more detail in Sections 3.3.2 and 3.3.3). Attribution studies have shown that there is *high confidence* that anthropogenic forcing has had a detectable influence on trends in global warming (*virtually certain* since the mid 20th century), in land warming on all continents except Antarctica (*likely* since the mid of the 20th century), ocean warming since 1970 (*very likely*) and in increases in hot extremes and decreases in cold extremes since the mid 20th century (*very likely*) (Bindoff et al., 2013a). In addition, there is *medium confidence* that anthropogenic forcing has contributed to increases in mean precipitation in the North-Hemisphere high-latitudes since the mid 20th century and to global-scale increases in heavy precipitation in land regions with sufficient observations over the same time period (Bindoff et al., 2013a). Schleussner et al. (2017) have shown from analyses of recent observed tendencies that changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred *(high confidence)*. The observed tendencies over that time frame are thus consistent with attributed changes since the mid-20th century (*high confidence*).

The next sections assess changes in several different types of climate-related hazards. It should be noted that the different types of hazards are considered in isolation, but that some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards (for instance sea level rise and heavy precipitation in some regions, possibly leading together to more flooding, or droughts and heatwaves, which can together increase the risk of fire occurrence). Such events, also called compound events, may substantially increase risks in some regions (e.g. (Amir et al., 2014; Van Den Hurk et al., 2015; Martius et al., 2016; Zscheischler et al., 2018). A detailed assessment of physically-defined compound events at 1.5°C vs 2°C global warming was not possible as part of this report, but aspects related to overlapping multi-sector risks are highlighted in Sections 3.4 and 3.5.

3.3.2 Regional temperatures on land, including extremes

3.3.2.1 Observed and attributed changes in regional temperature means and extremes

While the quality of temperature measurements obtained through ground observational networks tend to be high compared to that of measurements for other climate variables (Seneviratne et al., 2012), it should be noted that some regions are undersampled. Cowtan and Way (2014) highlighted issues regarding undersampling being concentrated at the poles and over Africa, which may lead to biases in estimated changes in GMST (see also Annex 3.1 S3-3 and Chapter 1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature. Despite this partly limited coverage, the attribution chapter of the AR5 (Bindoff et al., 2013a) and recent papers (e.g., Sun et al., 2016; Wan et al., 2018) assessed that over every continental regions and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century.

It is *very likely* that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale on land. It is also *likely* that consistent changes are detectable on continental scale in North America, Europe and Australia. This is consistent with the SREX and AR5 assessments (Seneviratne et al., 2012; Hartmann et al., 2013). There is *high confidence* that these observed changes in temperature extremes can be attributed to anthropogenic forcing (AR5, Bindoff et al., 2013a). As highlighted in Section 3.2, the observational record can be used to assess past changes associated with a global warming of 0.5°C. Schleussner et al. (2017) used this approach to assess observed changes in extreme indices for the 1991-2010 versus the 1960-1979 period, which corresponds to just about 0.5°C GMST difference in the observed record (based on the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) dataset, Hansen et al., 2010). They found that substantial changes due to 0.5°C warming are apparent for indices related to hot and cold extremes, as well as for the Warm Spell Duration Indicator (WSDI). In particular, they identified that one quarter of the land has experienced an intensification of hot extremes (maximum temperature in the hottest day of the year, TXx) by more than 1°C and a reduction of the intensity of cold extremes by at least 2.5°C (minimum temperature in the coldest night of the years, TNn). In addition, that study shows that half of the global land mass has experienced changes in WSDI of more than six days as well as an emergence of extremes outside the range of natural variability (Schleussner et al., 2017). Analyses from Schleussner et al. (2017) for temperature extremes are provided in the Annex 3-3 (Figure S3.6).

3.3.2.2 *Projected changes at 1.5°C versus. 2°C in regional temperature means and extremes*

There are several lines of evidence available for providing a regional assessment of projected change in temperature means and extremes at 1.5°C versus 2°C global warming (see Section 3.2). These include, analyses of changes in extremes as a function of global warming based on existing climate simulations using the Empirical Scaling Relationship (ESR) and variations therefrom (see Section 3.2 for details about the methodology) (e.g., Schleussner et al., 2017; Dosio and Fischer, 2018; Seneviratne et al., 2018c) dedicated simulations for 1.5°C versus 2°C global warming, for instance based on the Half a degree additional warming, prognosis and projected impacts (HAPPI) experiment (Mitchell et al., 2017) or other model simulations (e.g., Dosio et al., 2018); and analyses based on statistical pattern scaling approaches (e.g. Kharin et al., 2018). Results with these different lines of evidence display qualitatively consistent results regarding changes in temperature means and extremes at 1.5°C global warming compared to pre-industrial climate and 2°C global warming.

There are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C global warming, both in the global average (Schleussner et al., 2016b; Dosio et al., 2018; Kharin et al., 2018), as well as in nearly all inhabited land regions (Wartenburger et al., 2017; Seneviratne et al., 2018c; Wehner et al., 2018) (*high confidence)*. Temperatures over oceans display significant increases between 1.5°C and 2°C global warming (Figures 3.3 and 3.4). A general background on the available evidence on regional changes in temperature means and extremes at 1.5°C versus 2°C global warming is provided in the Annex 3.1 S3-3. As an example, Figure 3.5 shows for the IPCC SREX regions (Figure 3.2) regionally-based analyses of changes in the temperature of hot extremes as a function of warming (corresponding analyses for changes in the temperature of cold extremes are provided in the Annex 3.1 S3-3). As can be seen in these analyses, the mean response of the intensity of temperature extremes in climate models to changes in the global mean temperature is approximately linear and independent of the considered emission scenario (Seneviratne et al., 2016; Wartenburger et al., 2017). Nonetheless, in the case of changes in the number of days exceeding a given threshold, changes are found to be approximately exponential, with higher increases for rare events (Fischer and Knutti, 2015; Kharin et al., 2018); see for example, Figure 3.6. This behavior is consistent with a linear increase in absolute temperature for extreme threshold exceedances (Whan et al., 2015).

As mentioned in Section 3.3.1, there is an important land-sea warming contrast, with stronger warming on land (see also Christensen et al., 2013; Collins et al., 2013; Seneviratne et al., 2016), which implies that regional warming on land is generally higher than 1.5°C even when mean global warming is at 1.5°C. As highlighted in Seneviratne et al. (2016), this feature is generally stronger for temperature extremes (Figures 3.4 and 3.5; Annex 3.1 S3-3). For differences in regional temperature extremes at mean global warming of 1.5°C versus 2°C, this implies differences of as much as 1°C -1.5ºC in some locations, which are thus 2-3 times larger than the differences in global mean temperature. For hot extremes, the strongest warming is found in Central and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and Southern Africa (Figures 3.4 and 3.5). These regions are all characterized by a strong soil-moisture-temperature coupling (Vogel et al., 2017) leading to increased dryness and, consequently, a reduction in evaporative cooling and thus added warming in the projections. Some of these regions also show a wide range of responses to temperature extremes, in particular Central Europe and Central North America, due to discrepancies in the representation of the underlying processes in present climate models (Vogel et al., 2017). For mean temperature and cold extremes, the strongest warming is found in the northern high-latitude regions (*high confidence*). This is due to substantial ice-snow-albedo-temperature feedbacks (Figure 3.3 and Figure 3.4, middle), related to the known 'polar amplification' mechanism (e.g., IPCC, 2013; Masson-Delmotte et al., 2013).

Figure 3.7 displays maps of changes in the Number of Hot Days (NHD) at 1.5°C and 2°C GMST warming. Maps of changes in the number of Frost Days (FD) can be found in the Annex 3.1 S3-3. These analyses reveal clear patterns of changes between the two warming levels, also consistent with analysed changes in heatwave occurrence (e.g., Dosio et al., 2018). For the NHD, the largest differences are found in the tropics due to the lower interannual temperature variability (Mahlstein et al., 2011), and despite the tendency for higher absolute changes in hot temperature extremes in mid-latitudes (Figures 3.4 and 3.5). The emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). These analyses are consistent with other recent assessments. Coumou and Robinson (2013) find that under a 1.5°C warming, already 20% of the global land area, centered in low latitude regions, is projected to experience highly unusual monthly temperatures during boreal summers (a number which nearly doubles for 2°C of global warming).

Figure 3.8 includes an objective identification of "hot spots" / key risks in temperature indices subdivided by regions, based on the ESR approach applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Wartenburger et al., 2017). It is noted that results based on the HAPPI multi-model experiment (Mitchell et al., 2017) display similar results (Seneviratne et al., 2018c). The considered regions follow the classification of Figure 3.2 and also include the global land. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C versus 2°C. Based on these analyses, the following can be stated: Significant changes in responses are found in all regions, for most temperature indices, with the exception of i) the Diurnal Temperature Range (DTR) in most regions, of ii) Ice Days (ID), Frost Days (FD), and Growing Season Length (GSL) in mostly warm regions, and of iii) the minimum yearly value of the Maximum Daily Temperature (TXn) in very few regions. In terms of the sign of the changes, it can be seen that warm extremes display an increase in intensity, frequency and spell length (e.g. increase of the temperature of the hottest day of the year (TXx) in all regions, increase of proportion of days above 90th percentile of Tmax (TX90p) in all regions, increase of the length of the WSDI in all regions), while cold extremes display a decrease in intensity, frequency and spell length (e.g. increase of the temperature of the coldest night of the year (TNn) in all regions, decrease in the proportion of days below the 10th percentile of Tmin (TN10p), decrease in the length of the Cold Spell Duration Index (CSDI) in all regions). Hence, while warm extremes are intensified, it should also be noted that cold extremes become less intense and frequent (but have a higher temperatures) in affected regions.

Overall, large increases in hot extremes happen in many densely inhabited regions (Figure 3.5), both compared to present-day climate and at 2°C versus 1.5°C global warming. For instance, Dosio et al. (2018) concluded based on a modeling study that 13.8% of the world population would be exposed to severe heat waves at least once every 5 years under 1.5°C global warming, with a threefold increase (36.9%) under 2°C warming, i.e. a difference of about 1.7 billion people. They also conclude that limiting global warming to 1.5°C would result in about 420 million fewer people being frequently exposed to extreme heat waves, and about 65 million fewer people being exposed to exceptional heat waves. However, changes in vulnerability were not considered in that study.

In summary, there are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C global warming, both in the global average as well as in near all land regions[1] and the ocean (*likely*). Also, the observational record reveals that substantial changes due to a 0.5°C GMST warming are apparent for indices related to hot and cold extremes, as well as for the WSDI *(likely)*. A warming of 2°C versus 1.5°C leads to more frequent and more intense hot extremes in all land regions[1], as well as to longer warm spells, affecting many densely inhabited regions (*very likely*). Strongest increases in the frequency of hot extremes happens for the rarest events (*very likely*). On the other hand, cold extremes would become less intense and less frequent, and cold spells would be less extended (*very likely*). Temperature extremes on land generally increase more than the global average temperature (*very likely*). Extreme hot days in mid-latitudes display an up to two-fold higher warming than the GMST (*likely*). The highest levels of warming for extreme hot days are found in Central and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and Southern Africa (*likely*). These regions have a strong soil-moisture-temperature coupling in common, leading to increased dryness and, consequently, a reduction in evaporative cooling, although there is substantial model range in the representation of these processes, in particular in Central Europe and Central North America (*likely*). The coldest nights in high-latitudes warm by as much as 1.5°C for a 0.5°C increase in GMST, i.e. a three-fold higher warming (*likely*). The NHD shows the largest differences between 1.5°C and 2.0°C in the tropics because of their low interannual temperature variability (*likely*); the emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2ºC could result in around 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (*medium confidence*).

[1]FOOTNOTE: Using the SREX definition of regions (Figure 3.2)

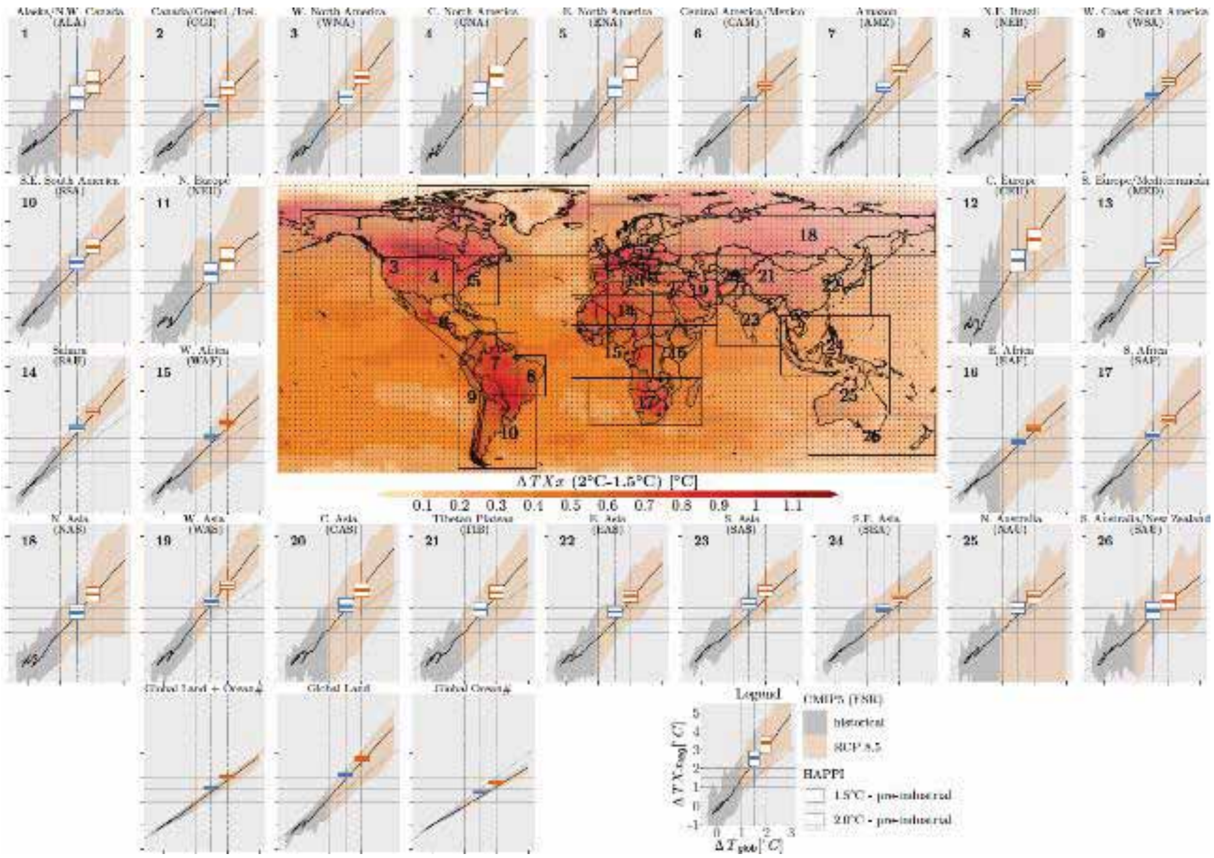


Figure 3.5: Projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming for IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (Figure 3.2), based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data (adapted from Seneviratne et al., 2016, and Wartenburger et al., 2017) together with projected changes from the Half a degree additional warming, prognosis and projected impacts (HAPPI) multi-model experiment (Mitchell et al., 2017, based on analyses in Seneviratne et al., 2018c) (bar plots on regional analyses and central plot, respectively). For analyses for other regions from Figure 3.2 (with asterisks), see Annex 3.1 S3-3. (The stippling indicates significance of the differences of changes in between 1.5°C and 2°C global warming based on all model simulations, using a two-sided paired Wilcoxon test (p = 0.01, after controlling the false discovery rate according to Benjamini and Hochberg, 1995). See Annex 3.1 S3-3 for details.

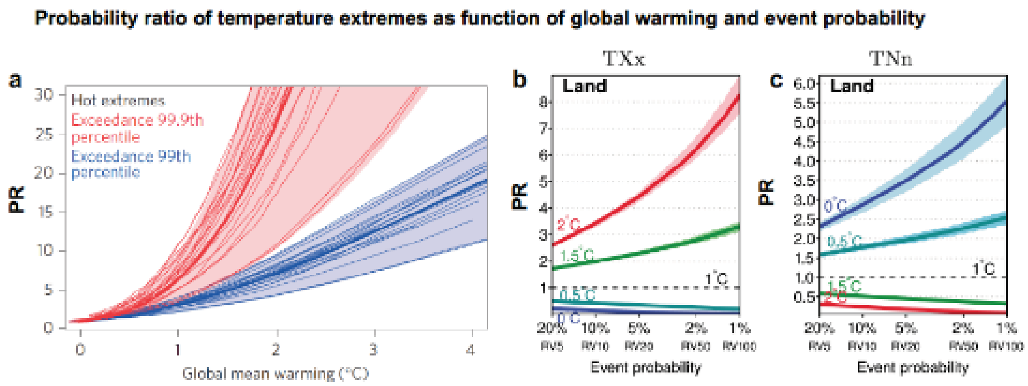


Figure 3.6: Probability ratio (PR) of exceeding extreme temperature thresholds. Left (a): PR of exceeding (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature at a given warming level relative to pre-industrial conditions averaged across land (from Fischer and Knutti, 2015). Middle (b) and right (c) : PR for hottest day of the year (TXx) and coldest night of the year (TNn) for different event probabilities (with RV indicating return values) in the current climate (1°C warming) ; the shading shows the interquartile (25%-75%) range (from Kharin et al., 2018).

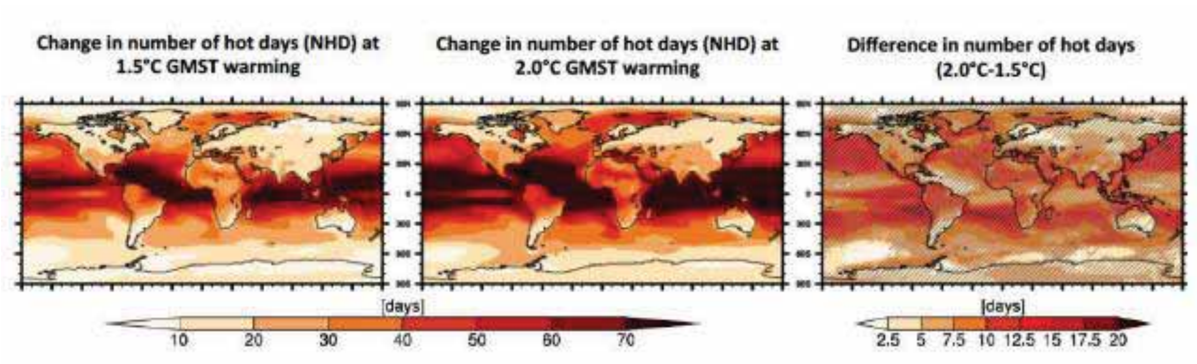


Figure 3.7: Projected change number of hot days (10% warmest days) at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Same underlying methodology and data basis as Figure 3.2 (Annex 3.1 S3-3 for more details).

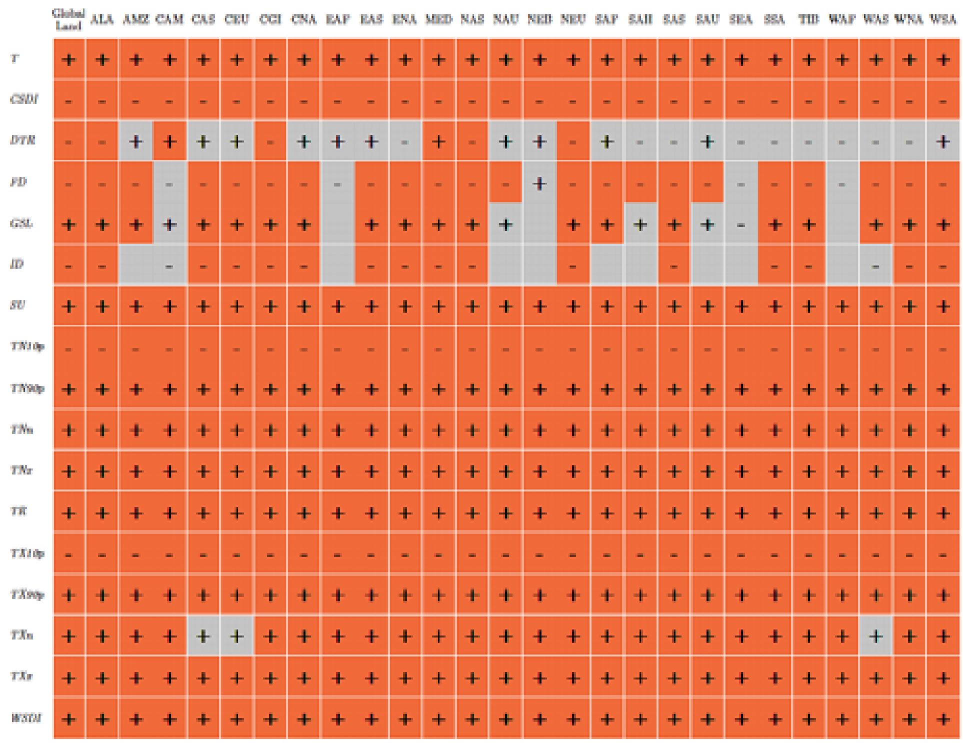


Figure 3.8: Significance of differences of regional mean temperature and range of temperature indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: T: mean temperature; CSDI: Cold Spell Duration Index; DTR: Diurnal Temperature Range; FD: Frost Days; GSL: Growing Season Length; ID: Ice Days; SU: Summer Days; TN10P: Proportion of days with minimum temperature (TN) below 10th percentile of TN; TN90p: Proportion of days with TN higher than 90th percentile TN; TNn: minimum yearly value of TN; TNx: maximum yearly value of TN; TR: Tropical Nights; TX10p: Proportion of days with maximum Temperature (TX) lower than 10th percentile of TX; TX90p: Proportion of days with TX higher than 90th percentile of TX; TXn: minimum yearly value of TX; TXx: maximum yearly value of TX; WSDI: Warm Spell Duration Index. Columns indicate analysed regions and global land (see Figure 3.2 for definition). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey shading. Note that decreases in CSDI, FD, ID, TN10p and TX10p are linked to increased temperatures in cold days or nights. Significance is tested using a two-sided paired Wilcoxon test (p=0.01, after controlling the false discovery rate according to Benjamini and Hochberg, 1995) (adapted from Wartenburger et al., 2017).

3.3.3 Regional precipitation, including heavy precipitation and monsoons

This section addresses regional changes in precipitation on land, with a focus on heavy precipitation and consideration of changes to the key features of monsoons.

3.3.3.1 Observed and attributed changes in regional precipitation

Observed global changes in the water cycle, including precipitation, are more uncertain than observed changes in temperature (Hartmann et al., 2013; Stocker et al., 2013). There is *high confidence* that mean precipitation over the mid-latitude land areas of the Northern Hemisphere has increased since 1951 (Hartmann et al., 2013). For other latitudinal zones area-averaged long-term positive or negative trends have *low confidence* due to data quality, data completeness or disagreement amongst available estimates (Hartmann et al., 2013). There is in particular *low confidence* regarding observed trends in precipitation in monsoon regions, based on the SREX report (Seneviratne et al., 2012), the AR5 (Hartmann et al., 2013), as well as on more recent publications (Singh et al., 2014; Taylor et al., 2017; Bichet and Diedhiou, 2018) Annex 3.1 S3-3).

For heavy precipitation, the AR5 (Hartmann et al., 2013), assessed that observed trends displayed more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation *(likely)*. In addition, it assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al., 2013a).

Regarding changes in precipitation associated with a global warming of 0.5°C, the observed record suggests that robust increases in observed precipitation extremes can be identified for annual maximum 1-day precipitation (RX1day) and consecutive 5-day precipitation (RX5day) for GMST changes of this magnitude (Schleussner et al., 2017) (Annex S3.3, Figure S3.7).

3.3.3.2 Projected changes at 1.5°C versus 2°C in regional precipitation

Figure 3.3 (Section 3.3.1) summarizes the projected changes in mean precipitation at 1.5°C versus 2°C. Some regions display substantial changes in mean precipitation between 1.5°C versus 2°C global warming, in particular decreases in the Mediterranean area, including Southern Europe, the Arabian Peninsula and Egypt. Some studies are also available for other regions across the world. For instance, Déqué et al. (2017) investigate the impact of a 2°C global warming on precipitation over tropical Africa and found that average precipitation does not show a significant response due to two compensating phenomena: (a) the number of rain days decreases whereas the precipitation intensity increases, and (b) the rainy season occurs later during the year with less precipitation in early summer and more precipitation in late summer. The assessment found insignificant differences between 1.5°C and 2°C scenarios for tropical Africa, which is consistent with the results of Figure 3.3. For Europe, for 2°C global warming, a robust increase of precipitation over Central and Northern Europe in winter and only over Northern Europe in summer, and decreases of precipitation in Central/Southern Europe in summer, with changes reaching 20% have been reported by Vautard et al. (2014) and is more pronounced than with +1.5°C global warming (Jacob et al., 2018).

For changes in heavy precipitation, Figure 3.9 displays projected changes in the 5-day maximum precipitation (Rx5day) as a function of global temperature increase, using a similar approach as in Figure 3.5. Further analyses are available in the Annex (Annex 3.1 S3-3). These analyses show that projected changes in heavy precipitation are more uncertain than for temperature extremes. However, the mean response of model simulations is generally robust and linear (see also Fischer et al., 2014; Seneviratne et al., 2016). As for temperature this response is also found to be mostly independent of the considered emissions scenario (e.g. Representative Concentration Pathway (RCP)2.6 versus RCP8.5; also Section 3.2). This appears to be a specific feature of heavy precipitation, possibly due to a stronger coupling with temperature, as the scaling of projections of mean precipitation changes with global warming shows some scenario dependency (Pendergrass et al., 2015).

The differences in heavy precipitation are generally small between 1.5°C and 2°C global warming (Figure

3.9 and Annex 3.1 S3-3 Figure S3.10). Some regions display substantial increases, for instance in Southern Asia, but generally in less than 2/3 of the CMIP5 models (Annex 3.1 S3-3, Figure S3.10). Wartenburger et al. (2017) suggests that for Eastern Asia, there are substantial differences in heavy precipitation at 1.5°C versus 2°C. Based on regional climate simulations, Vautard et al. (2014) found a robust increase in heavy precipitation everywhere in Europe and in all seasons, except Southern Europe in summer, consistent with the analysis of Jacob et al. (2014) which used more recent downscaled climate scenarios (EURO-CORDEX) and a higher resolution (12km) for +2°C global warming. There is a consistent agreement in the direction of change for +1.5°C global warming over much of Europe (Jacob et al., 2018). While there are variations between regions, the global tendency for heavy precipitation suggests an increase at 2°C versus 1.5°C (see also Fischer and Knutti, 2015), and Kharin et al., 2018), Figure 3.10, as well as Betts et al., 2018).

The AR5 assessed that the global monsoon, aggregated over all monsoon systems, is *likely* to strengthen, with increases in its area and intensity, while the monsoon circulation weakens (Christensen et al., 2013). There are a few publications that provide more recent evaluations on projections of changes in monsoons for high-emissions scenarios (e.g., Jiang and Tian, 2013; Jones and Carvalho, 2013; Sylla et al., 2015, 2016); Annex S3-3). However, given that a) scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the AR5 and these more recent studies, and b) the fact that there appears to be no specific assessment of changes in monsoon precipitation at 1.5°C versus 2°C global warming in the present literature, and c) that there is *low confidence* in observed trends in monsoons (Section 3.3.3.1), the present assessment is that there is *low confidence* regarding projected changes in monsoons at 1.5°C and 2°C global warming, as well as regarding differences in monsoon responses at 1.5°C versus 2°C.

Similarly, as for Figure 3.8, Figure 3.11 includes an objective identification of "hot spots" / key risks in heavy precipitation indices subdivided by regions, based on (Wartenburger et al., 2017). The considered regions follow the classification of the IPCC SREX report (Figure 3.2) and also include global land areas. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C versus 2°C. Hot spots displaying statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including China and Japan) and in Eastern North America. Results are less consistent for other regions. Note that analyses for meteorological drought (lack of precipitation) are provided in Section 3.3.4.

In summary, observations and projections for mean and heavy precipitation are less robust than for temperature means and extremes (*high confidence*). Observations show that there are more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation *(likely)*. Several regions display statistically significant differences in heavy precipitation at 1.5°C *vs*. 2°C warming (with stronger increase at 2°C), and there is a global tendency towards increases in heavy precipitation on land between these two temperature levels (*likely*). Overall, regions that display statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including China and Japan) and in Eastern North America (*medium confidence*). There is *low confidence* in projected changes in heavy precipitation at 1.5°C versus 2°C in other regions.

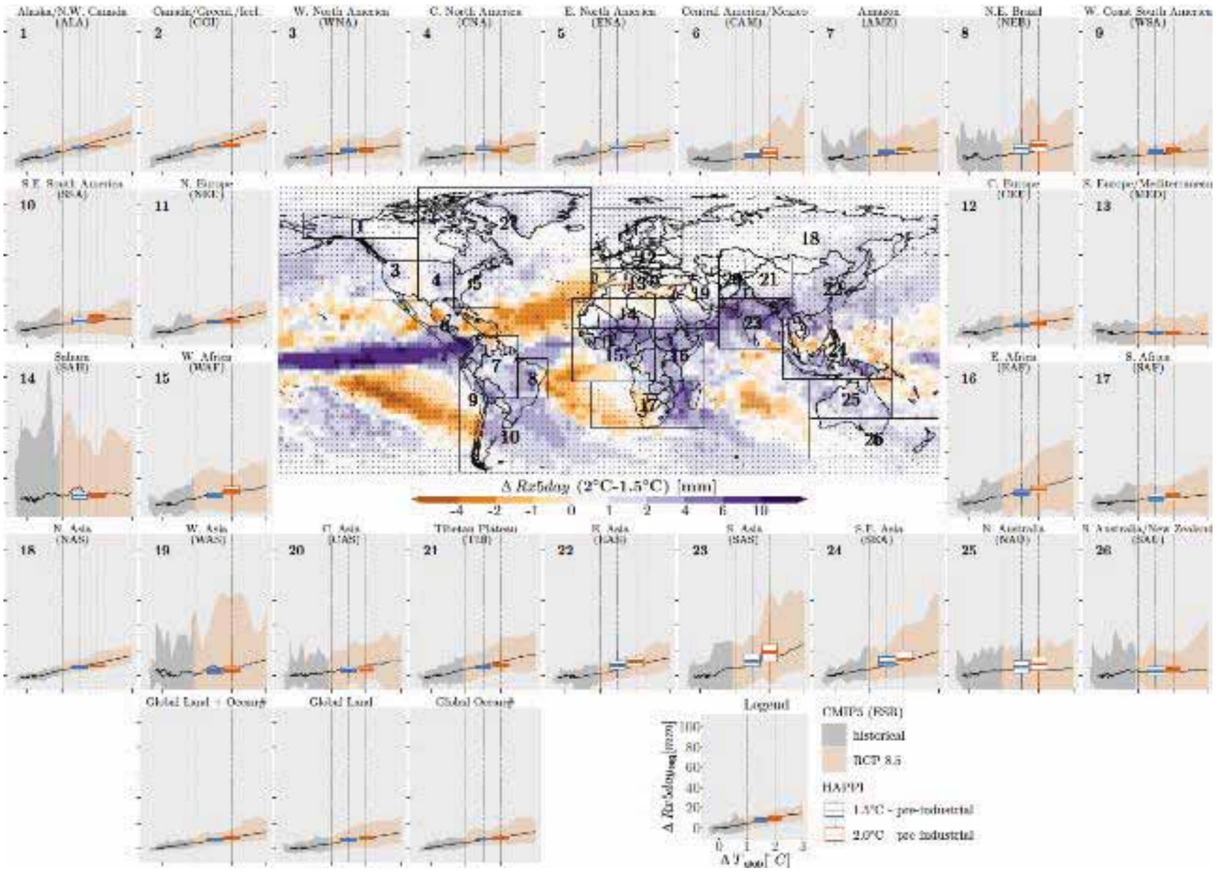


Figure 3.9: Projected changes in annual 5-day maximum precipitation (Rx5day) as function of global temperature warming for IPCC Special Report on the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (Figure 3.2), based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) together with projected changes from the HAPPI multi-model experiment (bar plots on regional analyses and central plot). Same data basis and analysis approach as in Figure 3.5 (Annex 3.1 S3-3 for more details).

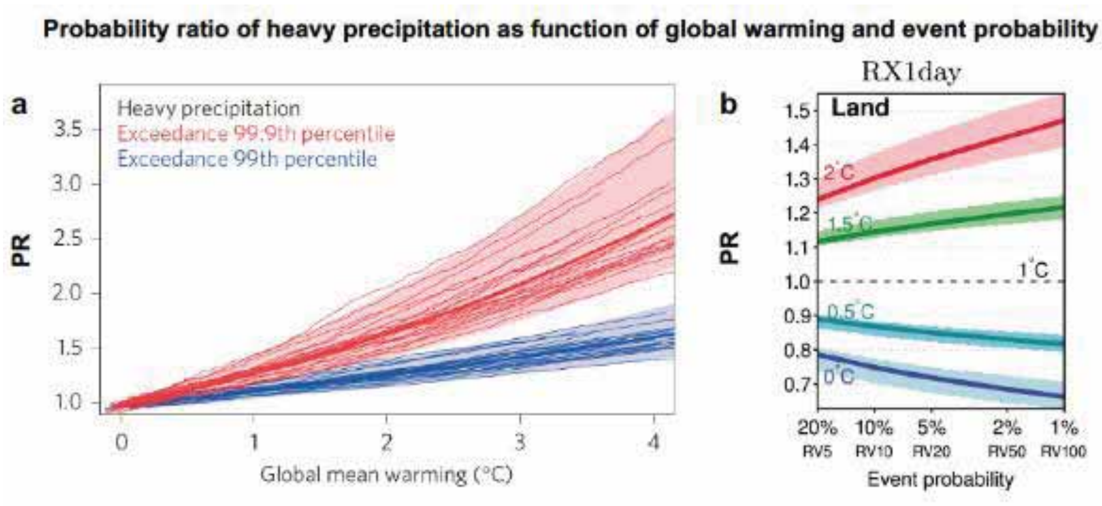


Figure 3.10: Probability ratio (PR) of exceeding extreme preciptiation (heavy precipitation) thresholds. (Left, a): PR of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily precipitation at a given warming level relative to pre-industrial conditions averaged across land (fromFischer and Knutti, 2015). (Right, b): PR for precipitation extremes (Rx1d) for different event probabilities (with RV indicating return values) in the current climate (1°C warming); the shading shows the interquartile (25%-75%) range (from Kharin et al., 2018).

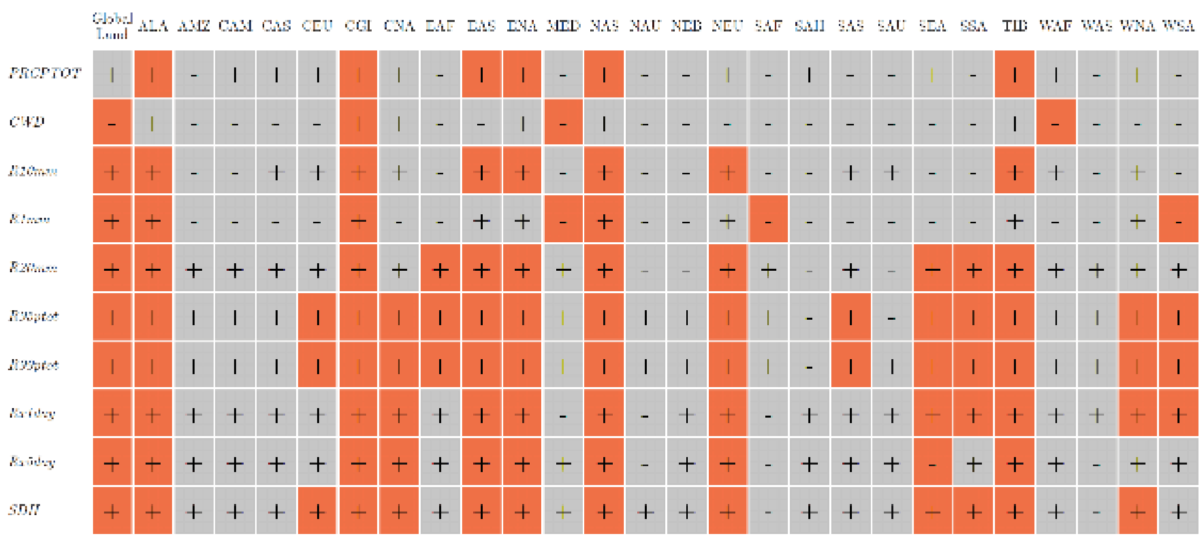


Figure 3.11: Significance of differences of regional mean precipitation and range of precipitation indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: PRCPTOT: mean precipitation; CWD: Consecutive Wet Days; R10mm: Number of days with precipitation > 10mm; R1mm: Number of days with precipitation>1mm; R20mm: Number of days with precipitation >20mm; R95ptot: Proportion of rain falling as 95th percentile or higher; R99ptot: Proportion of rain falling as 99th percentile or higher; RX1day: Intensity of maximum yearly 1-day precipitation; RX5day: Intensity of maximum yearly 5-day precipitation; SDII: Simple Daily Intensity Index. Columns indicate analysed

regions and global land (see Figure 3.3 for definition). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey shading. Same data basis and analysis approach as in Figure 3.8 (see Annex 3.1 S3-3 for more details).

3.3.4 Drought and dryness

3.3.4.1 Observed and attributed changes

The IPCC AR5 assessed that there was *low confidence* in the sign of drought trends since 1950 at global scale, but that there was *likely* to be trends in some regions of the world, including increases in drought in the Mediterranean and West Africa and decreases in droughts in central North America and north-west Australia (Hartmann et al., 2013; Stocker et al., 2013). The AR5 assessed that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013a) and did not provide assessments for the attribution of regional changes in droughts (Bindoff et al., 2013a).

The recent literature does not suggest a necessary revision of this assessment, except in the Mediterranean region. Recent publications based on observational and modeling evidence suggest that human emissions have substantially increased the probability of drought years in the Mediterranean region (Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017). There is also new evidence documenting consistent observed drying trends in the Eastern Mediterranean (Syria; see Box 3.2). Based on this evidence, there is *medium confidence* that enhanced greenhouse forcing contributed to increased drying in the Mediterranean region (including Southern Europe, Northern Africa and the Near-East) and that this tendency will thus continue to be increased under higher levels of global warming.

Box 3.1: Sub-Saharan Africa: Changes in Temperature and Precipitation Extremes

Sub-Saharan Africa has experienced the dramatic consequences of climate extremes becoming more frequent and more intense over the past decades (Paeth et al., 2010; Taylor et al., 2017). To reduce the adverse effects of climate change, all African countries signed the Paris Agreement and through their Nationally Determined Contributions (NDCs), they committed to contribute to the global effort of mitigation of Greenhouse Gas (GHG) emissions in the aim to hold global temperature increases to ‘well below 2 degrees’ and to pursue efforts to limit warming to ‘1.5 °C above preindustrial levels’. The target of limiting to 1.5°C above pre-industrial levels is a useful message to share the urgency, but it focused the climate change debate on a temperature threshold (Section 3.3.2), while the potential impacts of these global warming levels at local to regional scales on key sectors such as agriculture, energy, health, etc. remain uncertain in most regions and countries of Africa (Sections 3.3.3, 3.3.4, 3.3.5 and 3.3.6).

Weber et al. (2018) found that at regional scales, temperature increases in Sub-Saharan Africa are projected to be higher than the global mean temperature increase (at global warming of 1.5°C and at 2°C; Section 3.3.2 for further background and analyses of climate model projections). Even if the mean global temperature anomaly is kept below 1.5°C, regions between 15°S and 15°N are projected to experience an increase in hot nights as well as longer and more frequent heat waves (e.g., Kharin et al., 2018). Increases would be even larger if the global mean temperature reaches 2°C of global warming, with significant changes in the occurrence and intensity of temperature extremes in all Sub-Saharan regions (Sections 3.3.1 and 3.3.2; Figures 3.4, 3.5 and 3.8).

West and Central Africa display particularly large increases in the number of hot days, both at 1.5°C and 2°C global warming (Section 3.3.2). This is due to the relatively small interannual present-day variability, which implies that climate-change signals can be detected earlier (Mahlstein et al., 2011, Section 3.3.2). Changes in total precipitation exhibit several uncertainties, mainly in the Sahel (Diedhiou et al., 2018) Section 3.3.3 and Figure 3.8). In the Guinea Coast and Central Africa, a weak change in the total precipitation is noted though it is projected in most models (70%) a decrease of the length of wet spells and a slight increase of heavy rainfall. Western Sahel is projected by most models (80%) to experience the strongest drying with a significant increase in the maximum length of dry spells (Diedhiou et al., 2018). Above 2°C, this region could become more vulnerable to drought and could meet serious food security issues (Salem et al., 2017; Parkes et al., 2018) Cross-Chapter Box 6 and Section 3.4.6). West Africa has thus been identified as a climate-change hot spot with a likelihood of negative impact of climate change in crop yields and production (Cross-Chapter Box 6, Section 3.4.6; Sultan and Gaetani, 2016; Palazzo et al., 2017). Despite uncertainty in future projections of the precipitation in West Africa, which is essential for rain-fed agriculture, a robust evidence of yield loss might emerge. This yield loss is mainly driven by increased mean temperature while potential wetter or drier conditions as well as elevated CO_2 concentrations can modulate this effect (Roudier et al., 2011); see also Cross-Chapter Box 6 and Section 3.4.6). Using Representative Concentration Pathway (RCP)8.5 Cooridnated Regional Climate Downscaling Experiment (CORDEX) scenarios from 25 Regional Climate Models (RCMs) forced with different General Circulation Models (GCMs), Klutse et al. (2018) noted over West Africa a decrease of mean rainfall in models with larger warming at 1.5°C (Section 3.3.4) and Mba et al. (2018) found over Central Africa a lack of consensus in the changes in precipitation (Figure 3.8 and Section 3.3.4), though there is a tendency to a decrease of the maximum length of Consecutive Wet Days (CWD) and a significant increase of the maximum length of Consecutive Dry Days (CDD).

Over southern Africa, models agree in a positive sign of change for temperature, with temperature rising faster at 2°C (1.5ºC-2.5°C) compared to 1.5°C (0.5ºC - 1.5°C). Areas of the south-western region, especially in South Africa and parts of Namibia and Botswana are expected to experience the highest increases in temperature (Engelbrecht et al., 2015; Maúre et al., 2018; Section 3.3.2). The western part of southern Africa is projected to become drier with increasing drought frequency and number of heat waves towards the end of the 21st century (Engelbrecht et al., 2015; Dosio, 2017; Maúre et al., 2018) Section 3.3.4). At 1.5°C, a robust signal of precipitation reduction is found over the Limpopo basin and smaller areas of the Zambezi basin, in Zambia, as well as in parts of Western Cape, in South Africa, while an increase is projected over central and western South Africa as well as in southern Namibia (Section 3.3.4). At 2°C, the region is projected to face robust precipitation decreases of about 10-20% and increases in the length of CDD with longer dry spells projected over Namibia, Botswana, northern Zimbabwe and southern Zambia. Conversely, the length of CWD is projected to decrease with robust signals over Western Cape (Maúre et al., 2018). Projected reductions in stream flow between 5% and 10% in the Zambezi River Basin have been associated with increased evaporation and transpiration rates resulting from rise in temperature (Kling et al., 2014; Section 3.3.5) with issues on hydroelectric power across the southern African region.

Over Eastern Africa, Osima et al. (2018) found that annual rainfall projections show a robust wetting signal over Somalia and a less robust decrease over central and northern Ethiopia (Section 3.3.3). The length of CDD and CWD are projected to increase and decrease respectively (Section 3.3.4). These projected changes could impact the agricultural and water sectors in the region (Cross-Chapter Box 6 in this Chapter and Section 3.4.6).

[END BOX 3.1 HERE]

3.3.4.2 *Projected changes in drought and dryness at 1.5°C versus 2°C*

There is *medium confidence* in projections of changes in drought and dryness. This is partly consistent with the AR5, which assessed these projections as being '*likely* (*medium confidence*)' (Collins et al., 2013; Stocker et al., 2013). However, given the *medium confidence*, we assess that it does not seem suitable to provide a likelihood statement, consistent with the IPCC uncertainty guidance document (Mastrandrea et al., 2010) and the assessment of the IPCC SREX report (Seneviratne et al., 2012).The technical summary of the AR5 (Stocker et al., 2013) assessed that soil moisture drying in the Mediterranean, Southwest USA and southern African regions was consistent with projected changes in the Hadley circulation and increased surface temperatures and concluded that there was *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario. However, more recent assessments have highlighted uncertainties in dryness projections due to a range of factors, including variations between considered drought and dryness indices and the effects of enhanced CO_2 concentrations on plant water-use efficiency (Orlowsky and Seneviratne, 2013; Roderick et al., 2015). Overall, projections of changes in drought and dryness for high-emissions scenarios (e.g. RCP8.5 corresponding to about 4 °C global warming) are uncertain in many regions, despite the existence of a few regions displaying consistent drying in most assessments (e.g., Seneviratne et al., 2012; Orlowsky and Seneviratne, 2013). Uncertainty is expected to be even larger for conditions of smaller signal-to-noise ratio such as for global warming levels of 1.5°C and 2°C.

Some published literature is now available on the evaluation of differences in drought and dryness occurrence at 1.5°C and 2°C global warming for a) Precipitation-Evapotranspiration (P-E, i.e. as a general measure of water availability; Wartenburger et al., 2017; Greve et al., 2018), b) soil moisture anomalies (Lehner et al., 2017; Wartenburger et al., 2017), c) consecutive dry days (Schleussner et al., 2016b; Wartenburger et al., 2017), d) the 12-month Standardized Precipitation Index (Wartenburger et al. (2017), e) the Palmer-Drought Severity Index (Lehner et al., 2017), f) annual mean runoff (Schleussner et al., 2016b, see also next section). These analyses are overall consistent, despite the known sensitivity of drought assessment to chosen drought indices (see above paragraph).

Figure 3.12 in Greve et al. (2018) derives the sensitivity of regional changes in precipitation minus evapotranspiration to global temperature changes. The analysed simulations span the full range of available emissions scenarios and the sensitivities are derived using a modified pattern scaling approach. The applied approach assumes linear dependencies on global temperature changes while thoroughly addressing associated uncertainties via resampling methods. Northern high-latitude regions display robust responses towards increased wetness, while subtropical regions display a tendency towards drying but with a large range of responses. While the internal variability and the scenario choice play an important role in the overall spread of the simulations, the uncertainty stemming from the climate model choice usually dominates, accounting for about half of the total uncertainty in most regions (Wartenburger et al., 2017; Greve et al., 2018). The sign of projections, i.e. whether there might be increases or decreases in water availability under higher global warming, is particularly uncertain in tropical and mid-latitude regions. An assessment of the implications of limiting global mean temperature warming to values below (i) 1.5°C or (ii) 2°C shows that opting for the 1.5°C-target might slightly influence the mean response, but could substantially reduce the risk of experiencing extreme changes in regional water availability (Greve et al., 2018).

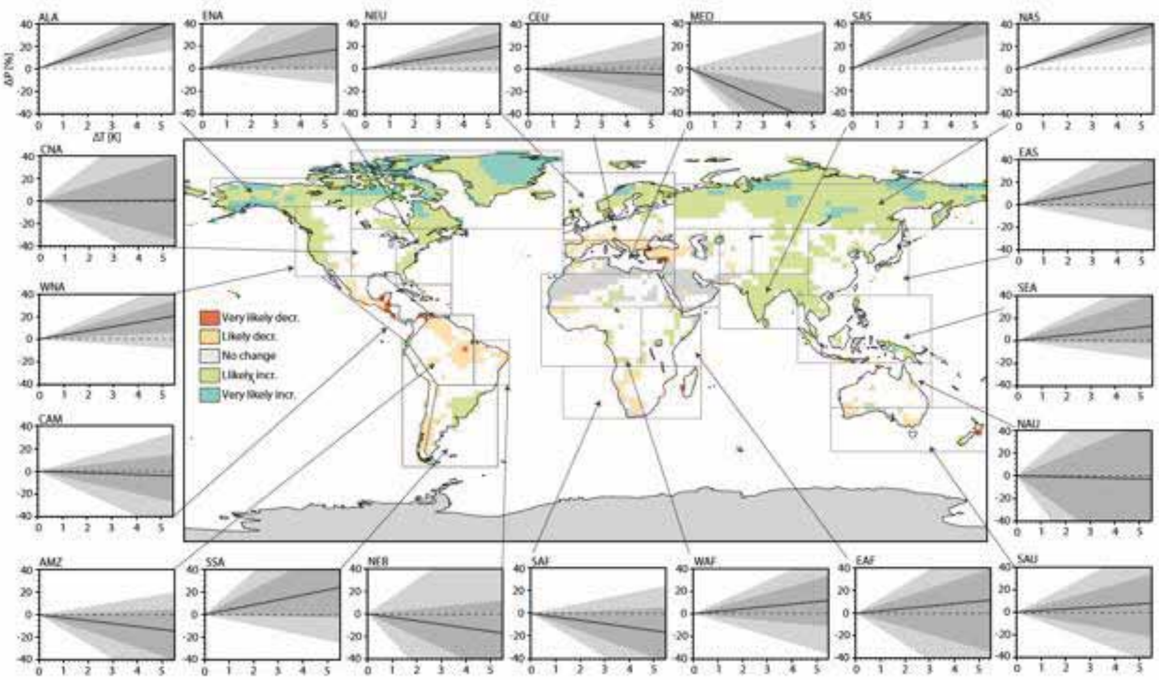


Figure 3.12: Summary of the likelihood of increases/decreases in Precipitation-Evapotranspiration (P-E) in Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations considering all scenarios and a representative subset of 14 climate models (one from each modeling center). Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a function of global mean temperature change averaged for most IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (see Figure 3.2) outlined in the map (from Greve et al., 2018).

The analysis for the mean response is also qualitatively consistent with results from Wartenburger et al. (2017), which use an ESR (Section 3.2) rather than pattern scaling for a range of drought and dryness indices, as well as with a recent assessment of Lehner et al. (2017) which consider changes in droughts assessed from the soil moisture changes and from the Palmer-Drought Severity Index. We note that these two further publications do not provide a specific assessment for changes in tails of the drought and dryness distribution. The conclusions of (Lehner et al., 2017) are that a) 'risks of consecutive drought years shows little change in the US Southwest and Central Plains, but robust increases in Europe and the Mediterranean', and that b) 'limiting warming to 1.5°C may have benefits for future drought risk, but such benefits are regional, and in some cases highly uncertain'.

Figure 3.13 displays projected changes in CDD as a function of global temperature increase, using a similar approach as in Figures 3.5 (based on Wartenburger et al., 2017). The analyses also include results from the HAPPI experiment (Mitchell et al., 2017). Again, the CMIP5-based ESR estimates and the results of the HAPPI experiment are found to agree well. We note the large disparity of responses depending on the considered regions.

Similarly as for Figures 3.8 and 3.11, Figure 3.14 includes an objective identification of "hot spots" / key risks in dryness indices subdivided by regions, based on (Wartenburger et al., 2017). This analysis reveals the following hot spots of drying, i.e. with increases in CDD, and decreases in P-E, Soil Moisture Anomalies (SMA), and SPI12, with at least two of the indices displaying statistically significant drying: the Mediterranean region (MED; including Southern Europe, northern Africa, and the Near-East) and Southern Africa. However, drying trends are also identified for single indices in Northeastern Brazil and Western South America. In addition, subregional drying trends are projected in the Western Sahel (see also Box 3.1) and in the Amazon region and Central America and Mexico (Fig. 3.12).

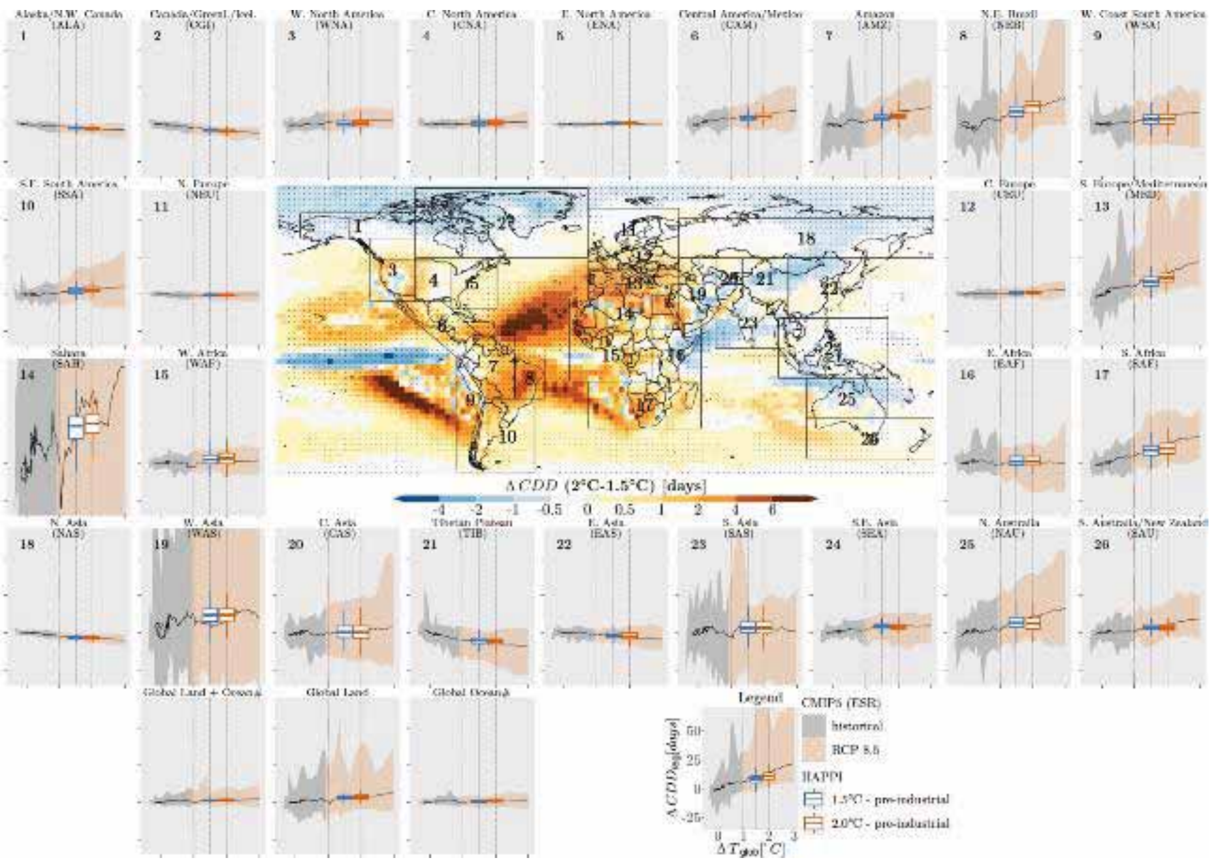


Figure 3.13: Projected changes in consecutive dry days (CDD) as function of global temperature warming for IPCC Special Report on Managng the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions, based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data together with projected changes from the HAPPI multi-model experiment (bar plots on regional analyses and central plot, respectively). Same data basis and analysis approach as in Figure 3.5 (Annex 3.1 S3-3 for more details).

	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
CDD	+	-	+	+	+	+	-	+	+	-	-	+	-	+	+	+	+	+	+	+	-	+	-	+	+	-	+
P − E	+	+	+	-	+	+	+	+	+	+	-	-	+	-	-	+	-	-	+	-	+	+	-	+	-	+	-
SMA	-	+	-	-	-	-	-	+	+	-	-	-	-	-	-	+	-	-	-	-	-	+	+	-	-	+	-
SPI12	+	+	-	+	+	+	+	+	-	+	+	-	+	-	-	+	-	-	-	-	+	-	+	-	-	+	+

Figure 3.14: Similar as Figures 3.8 and 3.11 but for changes in dryness indices. Significance of differences of regional drought and dryness indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: CDD: Consecutive Dry Days; P-E: Precipitation minus Evaporation; SMA: Soil Moisture Anomalies; SPI12: 12-month SPI. Columns indicate regions and global land (see Figure 3.2 for definitions). Significant differences are shown in light blue/brownshading (increases in indices indicated with + sign, decreases indicated with – sign; the light blue shading indicates decreases in dryness (decreases in CDD, or increases in P-E, SMA or SPI12) and the light brown shading indicates increases in dryness (increases in CDD, or decreases in P-E, SMA or SPI12). Insignificant differences are shown in grey shading. Same data basis and analysis approach as in Figure 3.7 (see Annex 3.1 S3-3 for more details).

Overall, the available literature, consistent with this analysis, reports particularly strong increases in dryness and decreases in water availability in Southern Europe and the Mediterranean when shifting from a 1.5°C to a 2°C global warming (Schleussner et al., 2016b; Lehner et al., 2017; Wartenburger et al., 2017; Greve et al., 2018; Samaniego et al., 2018; Figure 3.13). The fact that this is a region that is also already displaying substantial drying in the observational record (Seneviratne et al., 2012; Sheffield et al., 2012; Greve et al., 2014; Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017) provides additional evidence supporting this tendency, suggesting that it is a hot spot of dryness change above 1.5°C (see also Box 3.2). Some of the other identified hot spots, Southern Africa and Northeastern Brazil, are also consistently shown to display drying trends in other publications for higher levels of forcing (e.g., Orlowsky and Seneviratne, 2013), although there are so far to our knowledge no studies reporting observed drying trends in these regions. We thus form the consensus that there are substantial increases in risk of dryness (*medium confidence)* in both the Mediterranean region and South Africa at 2°C versus 1.5°C global warming, because these regions display significant changes in two dryness indicators (CDD and SMA) at these two global warming levels (Figure 3.14). There is *low confidence* elsewhere due to lack of consistency in analyses with different models or different dryness indicators. However, in many regions, there is *medium confidence* that most extreme risks of changes in dryness are avoided at 2°C versus 1.5°C (Figure 3.12).

In summary, in terms of drought and dryness, limiting global warming to 1.5ºC may substantially reduce the probability of extreme changes in water availability in some regions compared to changes for 2°C global warming (*medium confidence*). When shifting from 1.5 to 2°C, available studies and analyses suggest strong increases in dryness and reduced water availability in the Mediterranean region (including Southern Europe, northern Africa, and the Near-East) and in Southern Africa (*medium confidence*). Based on observations and model experiments, a drying trend is already detectable in the Mediterranean region, i.e. for a global warming of less than 1°C (*medium confidence*).

[START BOX 3.2 HERE]

Box 3.2: Mediterranean Basin and the Middle East Droughts

Human society has developed in tandem with the natural environment of the Mediterranean Basin over several millennia, laying the ground for diverse and culturally rich communities. Even if advances in technology may offer some protection from climatic hazards, the consequences of climatic change for inhabitants of the Mediterranean continue to depend on the long term interplay between an array of societal and environmental factors (Holmgren et al., 2016). This makes this region an example of strong vulnerability and various adaptation responses. Previous IPCC assessments and recent publications project regional changes in climate under increased warming, including consistent climate model projections of increased precipitation deficit amplified by strong regional warming (Seneviratne et al., 2012; Christensen et al., 2013; Collins et al., 2013; Greve and Seneviratne, 2015; Section 3.3.3).

A good example of such long history of resilience is the Eastern Mediterranean region, which has exhibited a strong negative trend in precipitation since 1960 (Mathbout et al., 2017) and experienced an intense and prolonged drought episode between 2007 and 2010 (Kelley et al., 2015). This drought was the longest and the most intense in the last 900 years (Cook et al., 2016). Some authors (e.g., Trigo et al., 2010; Kelley et al., 2015) assert that very low precipitation levels have driven a steep decline in agricultural productivity in the Euphrates and Tigris catchment basins, and displaced hundreds of thousands of people, mainly in Syria. Impacts have also been noticed on the water resource (Yazdanpanah et al., 2016) and the crop performance in Iran (Saeidi et al., 2017). Many historical periods of turmoil have coincided with severe droughts, for example the drought which occurred at the end of the Bronze Age, approximately 3200 years ago (Kaniewski et al., 2015). In this instance, a number of flourishing Eastern Mediterranean civilizations collapsed, and rural settlements re-emerged with agro-pastoral activities and limited long-distance trade. This illustrates how some vulnerable regions are forced to pursue drastic adaptive responses, including migration and societal structure changes.

The potential evolution of drought conditions under 1.5°C/2°C warming (Section 3.3.4) can be analyzed by comparing the 2008 drought (high temperature, low precipitation) with the 1960 drought (low temperature, low precipitation) (Kelley et al., 2015). Though the precipitation deficits were comparable, the 2008 drought was amplified by increased evapotranspiration induced by much higher temperatures (a mean increase of 1°C on the 1931-2008 period on Syria) and a large population increase (from 5 million in 1960 to 22 million in 2008). Koutroulis et al. (2013) projects that of the 18% decrease of water availability for Crete under a 2°C global warming at the end of the 21st century, only 6% is due to decreased precipitation (the rest is due to an increase in evapotranspiration). This study and others like it confirm an important risk of extreme drought conditions for the Middle East (even higher in continental locations than in islands) with a 1.5°C global warming (Jacob et al., 2018), consistent with current observed changes (Greve et al., 2014); Section 3.3.4). Risks of drying in the Mediterranean region can be substantially reduced if global warming is limited to 1.5°C compared to 2°C or higher levels of warming (Guiot and Cramer, 2016); see also Section 3.4.3). Higher warming levels may induce strong levels of vulnerability exacerbated by large changes in demography.

[END BOX 3.2 HERE]

3.3.5 Runoff and fluvial flooding

3.3.5.1 Observed and attributed changes in runof and river flooding

There has been progress since the AR5 in identifying historical changes in streamflow and continental runoff. Dai (2016) using available streamflow data shows that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the 200 world's major rivers with negative trends outnumbering the positive ones. Although streamflow trends are mostly non-statistically significant, they are consistent with observed regional precipitation changes. From 1950 to 2012, precipitation and runoff have increased over southeastern South America, central and northern Australia, the central and northeast United States, central and northern Europe, and most of Russia and decreased over most of Africa, East and South Asia, eastern coastal Australia, southeastern and northwestern United States, western and eastern Canada, the Mediterranean region and in some regions of Brazil (Dai, 2016).

A large part of the observed regional trends in streamflow and runoff could have resulted from internal multidecadal and multiyear climate variations, especially the Pacific Decadal Variability (PDV), the Atlantic Multidecadal Oscillation (AMO) and the El Niño-Southern Oscillation (ENSO) although the effect of anthropogenic greenhouse gasses and aerosols could also be important (Hidalgo et al., 2009; Gu and Adler, 2013, 2015; Chiew et al., 2014; Luo et al., 2016; Gudmundsson et al., 2017). Additionally, other human activities can influence the hydrological cycle such as land-use/land-cover change, modifications in river morphology and water table depth, construction and operation of hydropower plants, dikes and weirs, wetland drainage and agricultural practices such as water withdrawal for irrigation. All of these can also have a large impact on runoff at river basin scales although there is less agreement over their influence on global mean runoff (Gerten et al., 2008; Sterling et al., 2012; Hall et al., 2014; Betts et al., 2015; Arheimer et al., 2017). Some studies suggest that increases in global runoff resulting from changes in land-cover or land-use (predominantly deforestation) are counterbalanced by decreases from irrigation (Gerten et al., 2008; Sterling et al., 2012). Likewise, forest and grassland fires can also modify the hydrological response at a watershed scale when the burned area is significant (Versini et al., 2013; Springer et al., 2015; Wine and Cadol, 2016).

Few studies explore observed changes in extreme streamflow and river flooding since the IPCC AR5. Mallakpour and Villarini (2015) analyzed changes of flood magnitude and frequency in Central United States considering stream gauge daily records with at least 50 years of data ending no earlier than 2011. They showed that flood frequency has increased while there was limited evidence of a decrease in flood magnitude in this region. Stevens et al. (2016) found a rise in the number of reported floods in the United Kingdom during the period 1884-2013 with flood events appearing more frequently towards the end of the 20th century. A peak was identified in 2012 when annual rainfall was the second highest in over 100 years. Do et al. (2017) computed the trends in annual maximum daily streamflow data across the globe over the 1966–2005 period. They found decreasing trends for a large number of stations in western North America and Australia, and increasing trends in parts of Europe, eastern North America, parts of South America and southern Africa.

In summary, streamflow trends since 1950 are non-statistically significant in most of the world's largest rivers *(high confidence),* while flood frequency and extreme streamflow increased in some regions *(high confidence).*

3.3.5.2 Projected changes at 1.5°C versus 2°C in runoff and river flooding

Global-scale assessments of projected changes on freshwatr systems generally suggest that areas with either positive or negative changes in mean annual streamflow are smaller for 1.5°C than for 2°C global warming (Betts et al., 2018; Döll et al., 2018). Döll et al. (2018) found that only 11% of the global land area (excluding Greenland and Antarctica) shows statistically significant larger hazard at 2°C than at 1.5°C. Significant decreases are found for 13% of the global land area for both global warming levels, while significant increases are projected to occur for 21% of the global land area for 1.5°C, and rise to between 26% (Döll et al., 2018) and approximately 50% (Betts et al., 2018) for 2°C.

At the regional scale, projected runoff changes in general follow the spatial extent of projected changes in precipitation (see Section 3.3.3). Emerging literature shows runoff projections for different warming levels. For 2°C global warming, an increase in runoff is projected for much of the high northern latitudes, Southeast Asia, East Africa, north-eastern Europe, India, and parts of, Austria, China, Hungary, Norway, Sweden, the northwest Balkans, and Sahel (Schleussner et al., 2016b; Donnelly et al., 2017; Zhai et al., 2017; Döll et al., 2018). Addtionally, decreases are projected in the Mediterranean region, South Australia, Central America and Central and Southern South America (Schleussner et al., 2016b; Donnelly et al., 2017; Döll et al., 2018). Differences between 1.5°C and 2°C would be most prominent in the Mediterranean where the median reduction in annual runoff is expected to be about 9% (likely range 4.5–15.5%) at 1.5°C, while at 2°C warming, runoff could decrease by 17% (likely range 8–25%) (Schleussner et al., 2016b). Consistently, Döll et al. (2018) found that for an increase in global warming from 1.5°C to 2°C, statistically insignificant changes of the mean annual streamflow around the Mediterranean region become significant with decreases of 10–30%. Donnelly et al. (2017) found an intense decrease in runoff along both the Iberian and Balkan coasts as warming level increases.

Basin-scale projections of river runoff at different warming levels are available for many regions. Betts et al. (2018) assessed runoff changes in 21 of the world major river basins at 1.5°C and 2°C global warming (Figure 3.15). They found a general tendency towards increased runoff in the majority of the basins except in the Amazon, Orange, Danube and Guadiana basins where the range of projections indicate decreased mean flows (Figure 3.13). In the case of the Amazon, mean flows are projected to decline by up to 25% for 2°C global warming. Gosling et al. (2017) analyzed the impact of global warming of 1°C, 2°C and 3°C above pre-industrial levels on river runoff at catchment scale, focusing on eight major rivers in different continents: Upper Amazon, Darling, Ganges, Lena, Upper Mississippi, Upper Niger, Rhine and Tagus. Their results show that the sign and magnitude of change with global warming for the Upper Amazon, Darling, Ganges, Upper Niger and Upper Mississippi is unclear, while the Rhine and Tagus may experience decreases in projected runoff and the Lena may increase. Donnelly et al. (2017) analyzed the mean flow response to different warming levels for six major European rivers: Glomma, Wisla, Lule, Ebro, Rhine and Danube. Consistent with the increases in mean runoff in large parts of northern Europe, the Glomma, Wisla and Lule rivers could increase their discharges with global warming while the Ebro could decrease in part due to a decrease in runoff in southern Europe. In the case of the Rhine and Danube rivers, Donnelly et al. (2017) did not find clear results. Projected mean annual runoff of the Yiluo River catchment in northern China will decrease by 22% for 1.5°C and by 21% for 2°C, while the the mean annual runoff for the Beijiang River in southern China, is projected to increase by less than 1% and 3% in comparicon to the studied baseline period for 1.5°C and 2°C respectively (L. Liu et al., 2017). Chen et al. (2017) assessed the future changes of water resources in the Upper Yangtze River basin for the same warming levels and found a slight decrease in the annual discharge for 1.5°C which reverses sign for 2°C. Montroull et al. (2018) studied the hydrological impacts of the main rivers (Paraguay, Paraná, Iguazú and Uruguay) in La Plata basin in South America under 1.5°C and 2°C global warming and for two emission scenarios. The Uruguay basin shows increases in streamflow in all scenarios/warming targets except for the combination of RCP8.5/1.5°C warming. The increase is approximately 15% above the 1981–2000 reference period for 2°C global warming and the RCP4.5 scenario. For the other three rivers the sign of the change in mean streamflow highly depends on the RCP and GCM used.

Marx et al. (2018) analyzed how hydrological low flows in Europe are affected under different global warming levels (1.5°C, 2°C and 3°C). The Alpine region shows the strongest low flow increase from 22% for 1.5°C to 30% for 2°C because of the snow melt contribution, while in the Mediterranean low flows are expected to decrease due to the projected decreases in annual precipitation. Döll et al. (2018) found that extreme low flows in the tropical Amazon, Congo and Indonesian basins could decrease by 10% while in the southwestern part of Russia they could increase by 30% at 1.5°C. For 2°C, projected increases of extreme low flows are exacerbated in the higher northern latitudes and in eastern Africa, India and Southeast Asia while projected decreases intensify in the Amazon basin, Western United States, central Canada, and in Southern and Western Europe, although not in the Congo basin or Indonesia, where models show less agreement.

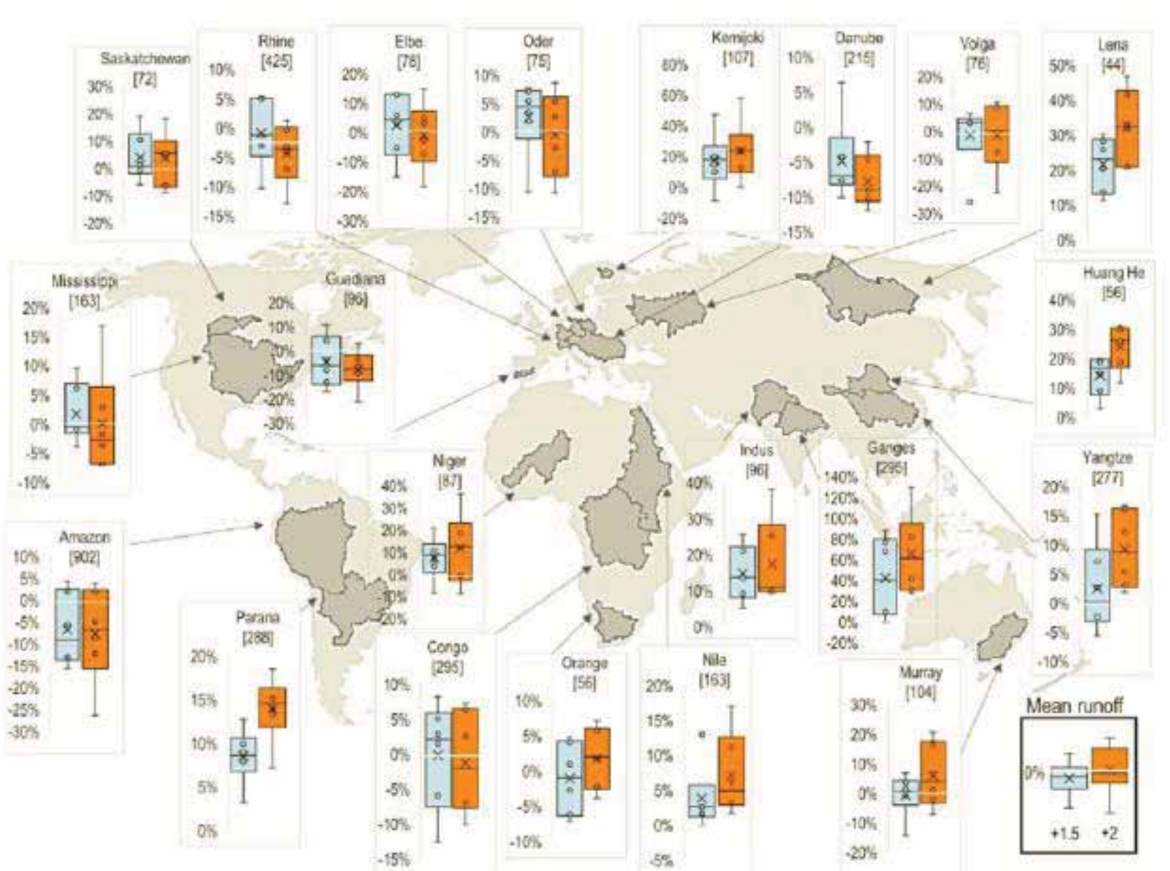


Figure 3.15: Runoff changes in twenty-one of the world major river basins at 1.5°C (blue) and 2°C (orange) global warming simulated by the Joint UK Land Environment Simulator (JULES) ecosystem–hydrology model under the ensemble of six climate projections. Boxes show the 25th and 75th percentile changes, whiskers

show the range, circles show the four projections that do not define the ends of the range, and crosses show the ensemble means. Numbers in square brackets show the ensemble-mean flow in the baseline (millimetres of rain equivalent) (from Betts et al., 2018).

Recent analysis of projections in river flooding and extreme runoff and flows are available for different global warming levels. At the global scale, Alfieri et al. (2017) assessed the frequency and magnitude of river floods and their impacts under 1.5°C, 2°C, and 4°C global warming scenarios. They found that flood events with occurrence interval larger than the return period of present flood protections are projected to increase in all continents under all considered warming levels, leading to widespread increment in the flood hazard. Döll et al. (2018) found that high flows are projected to increase significantly on 11% and 21% of the global land area at 1.5°C and 2°C respectively. Significantly increased high flows are expected to occur in South and Southeast Asia and Central Africa at 1.5°C which intensify under 2°C and include parts of South America.

At continental scale, Donnelly et al. (2017) and Thober et al. (2018) explored climate change impacts on European high flows and/or floods under 1.5°C, 2°C, and 3°C global warming. Thober et al. (2018) identified the Mediterranean region as a hotspot of change with significant decreases of −11% (-13%) in high flows at 1.5°C (2°C) mainly resulting from reduced precipitation (Box 3.2). In Northern regions, high flows are projected to rise between 1%-5% for 1.5°C and 2°C respectively due to increasing precipitation, although floods could decrease by 6% in both scenarios due to less snowmelt. Donnelly et al. (2017) found that high runoff levels could rise in intensity, robustness and spatial extent over large parts of continental Europe, with increasing warming level. For 2°C, flood magnitudes are expected to increase significantly in Europe south of 60°N, except for some regions (Bulgaria, Poland, southern Spain) while they are projected to decrease in most of Finland, northwestern Russia and northern Sweden, with the exception of southern Sweden and some coastal areas in Norway where floods may increase (Roudier et al., 2016). At basin scale, Mohammed et al. (2017) found that floods are projected to be more frequent and flood magnitudes greater at 2°C than at 1.5°C in the Brahmaputra River in Bangladesh.

In coastal regions, increases in heavy precipitation associated with tropical cyclones (Section 3.3.6) combined with increased sea levels (Section 3.3.9) may lead to increased flooding (Section 3.4.5).

In summary, there is *medium confidence* that a global warming of 2°C would lead to an expansion of the area with significant increases in runoff as well as of the area affected by flood hazard compared to conditions at 1.5°C global warming. A global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) as well as to an increase in flood hazard in some regions (*medium confidence*) compared to present day conditions.

3.3.6 Tropical cyclones and extratropical storms

Most recent studies on observed trends in the attributes of tropical cyclones are focusing on the satellite era starting in 1979 (Rienecker et al., 2011), but the study of observed trends is complicated by the heterogeneity of constantly advancing remote sensing techniques and instrumentation during this period (e.g., Landsea et al., 2006; Walsh et al., 2016). Numerous studies towards and beyond AR5 have reported a decreasing trend in the global number of tropical cyclones and/or the globally accumulated cyclonic energy (Emanuel, 2005; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Klotzbach and Landsea, 2015; Walsh et al., 2016). A theoretical physical basis for such a decrease to occur under global warming has recently been provided by Kang and Elsner (2015). However Klotzbach (2006), using a relatively short (twenty year) relatively homogeneous remotely sensed record reported no significant trends in global cyclonic activity, consistent with more recent findings of Holland and Bruyère (2014). Such contradictions, in combination with the fact that the almost four-decade long period of remotely sensed observations remains relatively short to distinguish anthropogenically induced trends from decadal and multi-decadal variability, implies that there is only *low confidence* regarding changes in global tropical cyclone numbers under global warming over the last four decades.

Studies on the detection of trends in the occurrence of very intense tropical cyclones (category 4 and 5 hurricanes on the Saffir-Simpson scale) over recent decades have yielded contradicting results. Most studies have reported increases in these systems (Emanuel, 2005; Webster et al., 2005; Klotzbach, 2006; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Walsh et al., 2016), and in particular for the North Atlantic, North Indian and South Indian Ocean basins (e.g., Singh et al., 2000; Singh, 2010; Kossin et al., 2013; Holland and Bruyère, 2014; Walsh et al., 2016). In the North Indian Ocean over the Arabian Sea, an increase in the frequency of extremely severe cyclonic storms has been reported and attributed to anthropogenic warming (Murakami et al., 2017). However, to the east over the Bay of Bengal, tropical cyclones and severe tropical cyclones have exhibited decreasing trends over the period 1961-2010, although the ratio between severe tropical cyclones and cyclones is increasing (Mohapatra et al., 2017). Moreover, studies that have used more homogeneous records but that were consequently limited to rather short periods of 20 to 25 years in length, have reported no statistically significant trends or decreases in the global number of these systems (Kamahori et al., 2006; Klotzbach and Landsea, 2015). CMIP5 model simulations of the historical period have also not produced anthropogenically induced trends in very intense tropical cyclones (Bender et al., 2010; Knutson et al., 2010, 2013; Camargo, 2013; Christensen et al., 2013), consistent with the findings of Klotzbach and Landsea (2015). There is consequently *low confidence* in the larger number of studies reporting increasing trends in the global number of very intense cyclones.

GCM projections of the changing attributes of tropical cyclones under high levels of greenhouse gas forcing (3°C to 4°C) are consistently indicating decreases in the global number of tropical cyclones (Knutson et al., 2010, 2015; Sugi and Yoshimura, 2012; Christensen et al., 2013; Yoshida et al., 2017). A smaller number of studies based on statistical downscaling methodologies are contradicting these findings, however, and are indicative of increases in the global number of tropical cyclones under climate change (Emanuel, 2017). Most studies also indicate increases in the global number of very intense tropical cyclones under high levels of global warming (Knutson et al., 2015; Sugi et al., 2017) consistent with dynamic theory (Kang and Elsner, 2015), although a few studies contradict this finding (e.g., Yoshida et al., 2017). Hence, we assess that under 3 to 4 °C of warming *it is more likely than not* (*medium confidence*) that the global number of tropical cyclones would decrease whilst the number of very intense cyclones would increase.

Only two studies have to date directly explored the changing tropical cyclone attributes under 1.5°C versus 2°C of global warming. Using a high resolution global atmospheric model, Wehner et al. (2017) concluded that the differences in tropical cyclone statistics under 1.5°C versus 2°C stabilization scenarios as defined by the HAPPI protocols (Mitchell et al., 2017) are small. Consistent with the majority of studies performed for higher degrees of global warming, the total number of tropical cyclones is projected to decrease under global warming, whilst the most intense (category 4 and 5) cyclones are projected to occur more frequently. These very intense storms are projected to be associated with higher peak wind speeds and lower central pressures under 2°C versus 1.5°C of global warming. The accumulated cyclonic energy is projected to decrease globally from 1.5 to 2 °C, in association with a decrease in the global number of tropical cyclones under progressively higher levels of global warming. It is also noted that heavy rainfall associated with tropical cyclones has been assessed in the IPCC SREX to *likely* increase under increasing global warming (Seneviratne et al., 2012). Two recent articles suggest that there is *high confidence* that global warming for present conditions (i.e. about 1°C of global warming, see Section 3.3.1) has increased the heavy precipitation associated with the 2017 Hurricane Harvey by about 15% or more (Risser and Wehner, 2017; van Oldenborgh et al., 2017). Hence, it can be inferred, under the assumption of linear dynamics, that further increases in heavy precipitation would occur under 1.5°C, 2°C and higher levels of global warming (*medium confidence*). Using a high resolution regional climate model, (Muthige et al., 2018) also explored the effects of different degrees of global warming on tropical cyclones over the southwest Indian Ocean, in transient simulations that downscaled a number of RCP8.5 GCM projections. Decreases in tropical cyclone frequencies are projected under both 1.5ºC and 2°C of global warming. The decreases in cyclone frequencies under 2°C global warming are somewhat larger than under 1.5°C of global warming, but with no further decreases projected under 3°C of global warming. This suggests that 2°C of warming, at least in these downscaling simulations, represent a type of stabilization level in terms of tropical cyclone formation over the southwest Indian Ocean and landfall over southern Africa (Muthige et al., 2018). There is thus *limited evidence* that the global number of tropical cyclones will be less under 2°C of global warming compared to 1.5 °C of warming, but with an increase in the number of very intense cyclones (*low confidence*).

The global response of the mid-latitude atmospheric circulation to 1.5 and 2°C of warming was investigated using the HAPPI ensemble with a focus on the winter season (Li et al., 2018). Under 1.5 °C of global warming a weakening of storm activity over North America, an equatorward shift of the North Pacific jet exit and an equatorward intensification of the South Pacific jet are projected. Under an additional 0.5°C of warming a poleward shift of the North Atlantic jet exit and an intensification on the flanks of the Southern Hemisphere storm track become more pronounced. The weakening of the Mediterranean storm track that is projected under low mitigation emerges in the 2 °C warmer world (Li et al., 2018). The AR5 (Stocker et al., 2013) assessed that under high greenhouse forcing (3°C or 4°C) there is *low confidence* in projections of poleward shifts of the North-Hemisphere storm tracks, while there is *high confidence* that there would be a small poleward shift of the South-Hemisphere storm tracks.In the context of this report, we assess that there is *limited evidence* and *low confidence* in whether any projected signal for higher levels of warming is to be well-manifested under 2°C of global warming.

3.3.7 Ocean circulation and temperature

It is *virtually certain* that the temperature of the upper layers of the ocean (0–700 m) has been increasing at a rate just behind that of the warming trend for the planet. The surface of three ocean basins have warmed over the period 1950–2016 (by 0.11°C, 0.07°C, and 0.05°C per decade for the Indian, Atlantic and Pacific oceans respectively; Hoegh-Guldberg et al., 2014, AR5 Chapter 30), with the greatest changes occurring at the highest latitudes. Isotherms (i.e. lines of equal temperature) of sea surface temperature (SST) are traveling to higher latitudes at rates of up to 40 km per year (Burrows et al., 2014; García Molinos et al., 2015). Long-term patterns of variability make detecting signals due to climate change complex, although the recent acceleration of changes to the temperature of the surface layers of the ocean has made the climate signal more distinct (Hoegh-Guldberg et al., 2014). There is also evidence of significant increases in the frequency of marine heatwaves in the observational record (Oliver et al., 2018), consistent with changes in mean ocean temperatures (*high confidence*). Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature as well as more intense patterns of climate variability (e.g., climate change intensification of ENSO). Increased heat in the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

Increasing land-sea temperature gradients, as induced by higher rates of continental warming compared to the surrounding oceans under climate change, have the potential to strengthen upwelling systems associated with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents) (Bakun, 1990). Observed trends support the conclusion that a general strengthening of longshore winds has occurred (Sydeman et al., 2014), but are unclear in terms of trends detected in the upwelling currents themselves (Lluch-Cota et al., 2014). Projecting the scale of the changes between 1°C and 1.5°C, and 1.5°C and 2°C is only informed by the changes over the past change in GMST of 0.5°C (*low confidence*). However, the weight of evidence from GCM projections of future climate change indicates the general strengthening of the Benguela, Canary and Humboldt upwelling systems under enhanced anthropogenic forcing (D. Wang et al., 2015) is *likely* to occur. This strengthening is projected to be stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in long-shore winds at higher latitudes, but at lower latitudes long-shore winds may decrease as a consequence of the poleward displacement of the subtropical highs under climate change (Christensen et al., 2007; Engelbrecht et al., 2009).

It is more likely than not that the Atlantic Meridional Overturning Circulation (AMOC) has been weakening in recent decades, given the detection of the cooling of surface waters in the north Atlantic and evidence that the Gulf Stream has slowed by 30% since the late 1950s (Srokosz and Bryden, 2015; Caesar et al., 2018). There is only *limited evidence* linking the current anomalously week state of AMOC to anthropogenic warming (Caesar et al., 2018). It is *very likely* that the AMOC will weaken over the 21st century. Best estimates and range for the reduction from CMIP5 are 11% (1 to 24%) in RCP2.6 and 34% (12 to 54%) in RCP8.5 (AR5). There is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5°C versus 2°C of global warming.

3.3.8 Sea ice

Summer sea ice in the Arctic has been retreating rapidly in recent decades. During the period 1997 to 2014 for example, the monthly mean sea-ice extent during September decreased on average by 130,000 km² per year (Serreze and Stroeve, 2015). This is about four times as fast as the September sea-ice loss during the period 1979 to 1996. Also sea-ice thickness has decreased substantially, with an estimated decrease in ice thickness of more than 50% in the central Arctic (Lindsay and Schweiger, 2015). Sea-ice coverage and thickness also decrease in CMIP5-model simulations of the recent past, and are projected to decrease in the future (Collins et al., 2013). However, the modeled sea-ice loss in most CMIP5 models is much weaker than observed. Compared to observations, the simulations are weak in terms of their sensitivity to both global mean temperature rise (Rosenblum and Eisenman, 2017) and to anthropogenic CO_2 emissions (Notz and Stroeve, 2016). This mismatch between the observed and modeled sensitivity of Arctic sea ice implies that the multi-model-mean response of future sea-ice evolution probably underestimates the sea-ice loss for a given amount of global warming. To address this issue, studies estimating the future evolution of Arctic sea ice tend to bias correct the model simulations based on the observed evolution of Arctic sea ice in response to global warming. Often based on such bias correction, pre-AR5 and post-AR5 studies agree that for 1.5 °C global warming relative to pre-industrial levels, the Arctic Ocean will maintain a sea-ice cover throughout summer for most years (Collins et al., 2013; Notz and Stroeve, 2016; Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Sigmond et al., 2018). For 2°C global warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Screen et al., 2018; Sigmond et al., 2018). The

Arctic is *very likely* to have experienced at least one ice-free Arctic summer after about 10 years of stabilized warming at 2°C compared to after about 100 years of stabilized warming at 1.5°C (Jahn, 2018; Screen et al., 2018; Sigmond et al., 2018). For a specific given year under stabilized warming of 2°C, studies based on large ensembles of simulations with a single model estimate the likelihood for ice-free conditions as 35% without a bias correction of the underlying model (Sanderson et al., 2017; Jahn, 2018); as between 10% and >99% depending on the observational record used to correct the sensitivity of sea ice decline to global warming in the underlying model (Niederdrenk and Notz, 2018); and as 19% based on a procedure to correct for biases in the climatological sea ice coverage in the underlying model (Sigmond et al., 2018). The uncertainty of the first year of the occurrence of an ice-free Arctic Ocean arising from internal variability is estimated to be about 20 years (Notz, 2015; Jahn et al., 2016).

The more recent estimates of the warming necessary to achieve an ice-free Arctic Ocean during summer are lower than the ones given in AR5 (about 2.6°C-3.1°C relative to preindustrial or 1.6°C-2.1°C global warming relative to the present day), which was similar to the estimate of 3°C relative to preindustrial levels (or 2°C global warming relative to the present day) by Mahlstein and Knutti (2012) based on bias-corrected CMIP3 models. Rosenblum and Eisenman (2016) explain why the sensitivity estimated by Mahlstein and Knutti (2012) might be too low, estimating instead that September sea ice in the Arctic disappears for 2°C relative to preindustrial (or about 1°C global warming relative to the present day), in line with the other recent estimates. Notz and Stroeve (2016) use the observed correlation between September sea-ice extent and cumulative CO_2 emissions to estimate that the Arctic Ocean would become nearly sea-ice-free during September with a further 1000 Gt of emissions, which also implies a sea-ice loss at about 2°C global warming. Some of the uncertainty in these numbers derives from the possible impact of aerosols (Gagne et al., 2017) and of volcanic forcing (Rosenblum and Eisenman, 2016). During winter, little Arctic sea ice is projected to be lost for either 1.5°C or 2ºC global warming (Niederdrenk and Notz, 2018).

Regarding the behavior of Arctic sea ice under decreasing temperatures following a possible overshoot of a long-term temperature target, a substantial number of pre-AR5 studies have found that there is no indication of hysteresis behavior of Arctic sea ice (Holland et al., 2006; Schroeder and Connolley, 2007; Armour et al., 2011; Sedláček et al., 2011; Tietsche et al., 2011; Boucher et al., 2012; Ridley et al., 2012). In particular, the relationship between Arctic sea-ice coverage and GMST is found to be indistinguishable between a warming scenario and a cooling scenario. These results have been confirmed by post-AR5 studies (Li et al., 2013; Jahn, 2018), which implies *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea-ice coverage.

In the Antarctic, sea ice shows regionally contrasting trends, with for example strongly decreased sea-ice coverage near the Antarctic peninsula and increased sea-ice coverage in the Amundsen Sea (Hobbs et al., 2016). Averaged over these contrasting regional trends, there has been a slow long-term increase in overall sea-ice coverage in the Southern Ocean, with, however, comparably low ice coverage from September 2016 onwards. Collins et al. (2013) have *low confidence* in Antarctic sea ice projections because of the wide range of model projections and an inability of almost all models to reproduce observations such as the seasonal cycle, interannual variability and the long-term slow increase. No studies are hence available to robustly assess the possible future evolution of Antarctic sea ice under low-warming scenarios.

In summary, the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C compared to 1.5°C global warming relative to pre-industrial levels and it is *very likely* that there will be the least one sea-ice-free Arctic summer after about 10 years of stabilized warming at 2°C, while about 100 years are required for a sea-ice-free Arctic summer at 1.5°C. There is *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea-ice coverage.

3.3.9 Sea level

Sea level varies over a wide range of temporal and spatial scales, which can be divided into three broad categories. These are Global Mean Sea Level (GMSL), regional variation about this mean, and the occurrence of sea-level extremes associated with storm surges and tides. GMSL has been rising since the late 19[th] century from the low rates of change that characterized the previous two millennia (Church et al., 2013). Slowing in the reported rate over the last two decades (Cazenave et al., 2014) may be attributable to instrumental drift in the observing satellite system (Watson et al., 2015) and volcanoes (Fasullo et al., 2016). Accounting for the former results in rates (1993 to mid-2014) of between 2.6 and 2.9 mm yr^{-1} (Watson et al., 2015). The relative contributions from thermal expansion, glacier and ice-sheet mass loss, as well as freshwater storage on land, are relatively well understood (Church et al., 2013; Watson et al., 2015) and there attribution is dominated by anthropogenic forcing since 1970 (15±55% before 1950, 69±31% after 1970) (Slangen et al., 2016).

There has been a significant advance in the literature since AR5, which has seen the development of Semi-Empirical Models (SEMs) into a broader emulation-based approach (Kopp et al., 2014; Mengel et al., 2016; Nauels et al., 2017) that is partially based on the results from more detailed, process-based modelling, where available. Church et al. (2013) assigned *low confidence* to SEMs because of their assumption that the relation between climate forcing and GMSL is the same in the past (calibration) and future (projection). Probable future changes in the relative contributions of thermal expansion, glaciers and (in particular) ice sheets invalidate this assumption, however recent emulation-based studies overcome this by considering individual GMSL contributors separately and are therefore employed in this assessment. In this subsection, the process-based literature of individual contributors to GMSL is considered for scenarios close to 1.5ºC and 2ºC before assessing emulation-based approaches.

A limited number of processes-based studies are relevant to GMSL in 1.5ºC and 2ºC worlds. Marzeion et al. (2018) force a global glacier model with temperature-scaled scenarios based on RCP2.6 to investigate the difference between 1.5ºC and 2ºC and find little difference between scenarios in the glacier contribution to GMSL at 2100 (54-97 mm relative to present day for 1.5ºC, and 63-112 mm for 2ºC using a 90% confidence interval). This arises because melt during the remainder of the century is dominated by the response to warming from preindustrial to present-day levels (in turn a reflection of the slow response times of glaciers). Fuerst et al. (2015) make projections of Greenland ice sheet's contribution to GMSL using an ice-flow model forced by the regional climate model Modèle Atmosphérique Régional (MAR, considered by Church et al., 2013) to be the 'most realistic' such model). They obtain an RCP2.6 range of 24-60 mm (1 standard deviation) by the end of the century (relative to 2000 and consistent with the assessment of Church et al. (2013)), however their projections do not allow the difference between 1.5ºC and 2ºC worlds to be evaluated.

The Antarctic ice sheet can contribute both positively and negatively to future GMSL rise by, respectively, increases in outflow (solid ice lost directly to the ocean) and increases in snowfall (due to the increased moisture-bearing capacity of a warmer atmosphere). Frieler et al. (2015) suggest a range of 3.5-8.7 % K^{-1} for this effect, which is consistent with the AR5. Observations from the Amundsen Sea sector of Antarctic suggest an increase in outflow (Mouginot et al., 2014) over recent decades associated with grounding line retreat (Rignot et al., 2014) and the influx of relatively warm Circumpolar Deepwater (Jacobs et al., 2011). Literature on the attribution of these change to anthropogenic forcing is still in its infancy (Goddard et al., 2017; Turner et al., 2017a). RCP2.6-based projections of Antarctic outflow (Levermann et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016, who include snowfall changes) are consistent with the AR5 assessment of Church et al. (2013) for end-of-century GMSL for RCP2.6, and do not support substantial additional GMSL rise by Marine Ice Sheet Instability or associated instabilities (see Section 3.6). While agreement is relatively good, concerns about the numerical fidelity of these models still exist and this may affect the quality of their projections (Drouet et al., 2013; Durand and Pattyn, 2015). An assessment of Antarctic contributions beyond the end of the century, in particular related to the Marine Ice Sheet Instability, can be found in Section 3.6.

While some literature on process-based projections of GMSL at 2100 is available, it is insufficient to distinguish between emission scenarios associated with 1.5ºC and 2ºC worlds. This literature is, however, consistent with Church et al. (2013) assessment of a *likely* range of 0.28-0.61 m at 2100 (relative to 1986-2005) suggesting that AR5 assessment is still appropriate. Recent emulation-based studies show convergence towards this AR5 assessment (Table 3.1) and offer the advantage of allowing a comparison between 1.5ºC and 2ºC worlds. Table 3.1 presents a compilation of both recent emulation-based and SEM studies.

Table 3.1: Compilation of recent projections for sea level at 2100 (in cm) for Representative Concentration Pathway (RCP)2.6, and 1.5 and 2.0 °C scenarios. Upper and lower limits are shown for the 17-84% and 5-95% confidence intervals quoted in the original papers.

Study	Baseline	RCP2.6		1.5ºC		2ºC	
		67%	90%	67%	90%	67%	90%
AR5	1986-2005	28-61					
Kopp et al. (2014)	2000	37-65	29-82				
Jevrejeva et al. (2016)	1986-2005		29-58				
Kopp et al. (2016)	2000	28-51	24-61				
Mengel et al. (2016)	1986-2005	28-56					
Nauels et al. (2017)	1986-2005	35-56					
Goodwin et al. (2017)	1986-2005		31-59 45-70 45-72				
Schaeffer et al. (2012)	2000		52-96		54-99		56-105
Schleussner et al. (2016b)	2000			26-53		36-65	
Bittermann et al. (2017)	2000				29-46		39-61
Jackson et al. (2018)	1986-2005			30-58 40-77	20-67 28-93	35-64 47-93	24-74 32-117
Sanderson et al. (2017)					50-80		60-90
Nicholls et al. (2018)	1986-2005				24-54		31-65
Rasmussen et al. (2018)	2000			35-64	28-82	39-76	28-96
Goodwin et al. (2018)	1986-2005				26-62		30-69

There is little consensus between the reported ranges of GMSL rise (Table 3.1), in particular at their upper limit, however there is *medium agreement* that GMSL at 2100 would be 0-0.2 m higher in a 2ºC world compared to 1.5 ºC with a most likely value of 0.1 m. There is *medium confidence* in this assessment because of issues associated with both projections of the Antarctic contribution to GMSL that are employed in emulation-based studies (see above) and the issues previously identified with SEMs (Church et al., 2013).

Translating projections of GMSL to the scale of coastlines and islands requires two further steps. The first accounts for regional changes associated with changing water and ice loads (such as Earth's gravitational field and rotation, and vertical land movement), as well as accounting for spatial differences in ocean heat uptake and circulation. The second maps regional sea level on to changes in the return periods of particular flood events to account for effects not included in global climate models such as tides, storm surges and wave setup and runup. Kopp et al. (2014) present a framework to do this and give an example application for nine sites (in the US, Japan, northern Europe and Chile). Of these sites, seven (all except those in northern Europe) experience at least a quadrupling in the number of years in the 21st century with 1-in-100 year floods under RCP2.6 compared to no future sea-level rise. Rasmussen et al. (2018)(2018) use this approach to investigate the difference between 1.5ºC and 2ºC worlds up to 2200. They find that the reduction in the frequency of 1-in-100 year floods in 1.5ºC compared to 2ºC worlds is greatest in the eastern US and Europe, with ESL event frequency amplification being reduced by about a half and with smaller reductions for Small Island Developing States (SIDS). This latter contrasts with the finding of Vitousek et al. (2017) that regions with low variability in extreme water levels (such as SIDS in the tropics) are particularly sensitive to GMSL rise such that a doubling of frequency may be expected for even small (0.1-0.2 m) rises. Schleussner et al. (2011) emulate the AMOC based on a subset of CMIP-class climate models. When forced using global temperatures appropriate to the CP3-PD scenario (1ºC warming at 2100 relative to 2000 or ~2 ºC relative to preindustrial), the emulation suggests an 11% median reduction in AMOC strength at 2100 (relative to 2000) with associated 0.04 m dynamic sea-level rise along the New York City coastline.

In summary, there is *medium confidence* that GMSL rise will be about 0.1 m less by the end of the century in a 1.5°C compared to a 2ºC warmer world. SLR beyond 2100 is discussed in 3.6, however recent literature strongly supports Church et al. (2013)'s assessment that sea level rise will continue well beyond 2100.

[START BOX 3.3 HERE]

Box 3.3: Lessons from Past Warm Climate Episodes

Climate projections and associated risk assessments for a future warmer world are based on climate model simulations. However, Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models do not include all existing earth system feedbacks and may therefore underestimate both rates and extents of changes (Knutti and Sedláček, 2012). Evidence from natural archives of three moderately warmer (1.5ºC-2°C) climate episodes in Earth's past help to assess such long-term feedbacks (Fischer et al., 2018).

While evidence over the last 2000 yr and during the Last Glacial Maximum (LGM) has been discussed in detail in the IPCC Fifth Assessment Report (Masson-Delmotte et al., 2013), the climate system response during past warm intervals was the focus of a recent review paper (Fischer et al., 2018) summarized in this Box. Examples of past warmer conditions (with essentially modern physical geography) include the Holocene Thermal Maximum (HTM) (broadly defined as about10-5 kyr before present (BP), where present is defined as 1950), the Last Interglacial (LIG about 129-116 kyr BP) and the Mid Pliocene Warm Period (MPWP, 3.3-3.0 millions years BP).

The global temperature response to changes in the insolation forcing during the HTM (Marcott et al., 2013) and the LIG (Hoffman et al., 2017) was up to +1°C warmer than preindustrial (1850-1900); high-latitude warming was 2-4°C (Capron et al., 2017), while temperature in the tropics changed little. Both HTM and LIG experienced atmospheric CO_2 levels similar to preindustrial conditions (Masson-Delmotte et al. 2013). During the MPWP, the most recent time period when CO_2 concentrations were similar to present, the global temperature was >1°C and Arctic temperatures about 8°C warmer than preindustrial (Brigham-Grette et al., 2013).

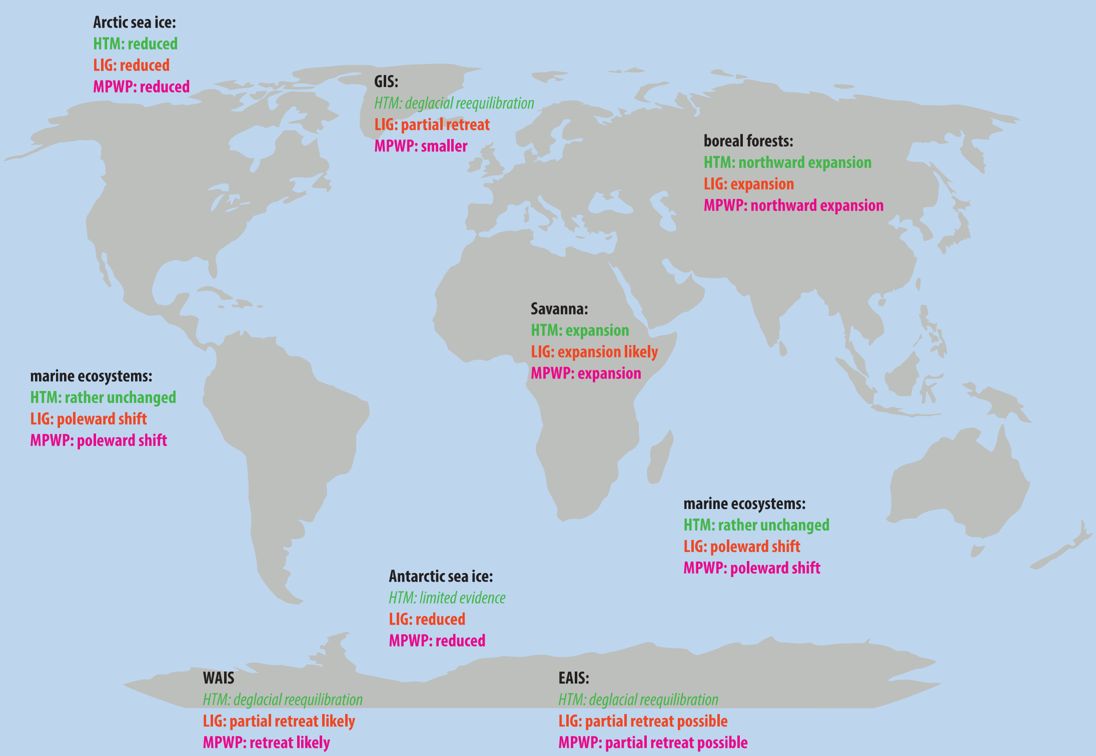
Although imperfect as analogs for the future, these regional changes can inform risk assessments such as the potential for crossing irreversible thresholds or amplifying anthropogenic changes (Box 3.3 Figure 1). For example, HTM and LIG Greenhouse Gas (GHG) concentrations show no evidence of runaway greenhouse gas releases under limited global warming. Transient releases of CO_2 and CH_4 may follow permafrost melting, but may be compensated by peat growth over longer timescales (Yu et al., 2010) . Warming may release CO_2 by enhancing soil respiration, counteracting CO_2 fertilization of plant growth (Frank et al., 2010). Evidence of a collapse of the Atlantic Meridional Overturning Circulation (AMOC) during these past events of limited global warming could not be found (Galaasen et al., 2014).

Ecosystems and biome (major ecosystem types) distributions changed significantly with warming both in the ocean and on land. For example, during past warming events some tropical and temperate forests retreated due to increased aridity, while savannas expanded (Dowsett et al., 2016). Poleward shifts of marine and terrestrial ecosystems, upward shifts in Alpine regions, and reorganisations of marine productivity are also recorded in natural archives (Williams et al., 2009; Haywood et al., 2016).

Past warm events are associated with partial sea ice loss in the Arctic. Limited data on Antarctic sea ice so far preclude firm conclusions about southern-hemisphere sea ice losses (de Vernal et al., 2013).

Reconstructed global sea level rise of 6-9 m during the LIG and possibly > 6m during the MPWP requires a retreat of either the Greenland or Antarctic ice sheets (or both) (Dutton et al., 2015). While ice sheet and climate models allow for a substantial retreat of the West Antarctic Ice Sheet (WAIS) and parts of East Antarctic Ice Sheet (DeConto and Pollard, 2016), direct observational evidence is still lacking. Evidence for ice retreat in Greenland is stronger, although a complete collapse of the Greenland ice sheet during the LIG can be excluded (Dutton et al., 2015). Under modest warming past sea levels rise rates were similar or up to two times larger than observed over the past two decades (Kopp et al., 2013). Given the long timescales involved to reach equilibrium in a warmer world, sea level rise will likely continue for millennia even if warming is limited to 2°C.

Finally, temperature reconstructions from these past warm intervals suggest that current climate models underestimate regional warming at high latitudes (polar amplification) and long-term (multi-millennial) global warming. None of these past warm climate episodes experienced the high speed of change in atmospheric CO_2 and temperatures that we are experiencing today (Fischer et al., 2018).



Box 3.3, Figure 1 : Impacts and responses of components of the Earth System. Summary of typical changes found for warmer periods in the paleorecord as discussed in Fischer et al. (2018) (all statements relative to pre-industrial. Statements in italic indicate that no conclusions can be drawn for the future). Note that significant spatial variability and uncertainty exists in the assessment of each component and, therefore, this figure should not be referred to without reading the source publication in detail. HTM: Holocene Thermal Maximum, LIG: Last Interglacial, MPWP: Mid Pliocene Warm Period

[END BOX 3.3 HERE]

3.3.10 Ocean chemistry

Ocean chemistry includes pH, salinity, oxygen, CO_2, and a range of other ions and gases, which affected by precipitation, evaporation, storms, river run-off, coastal erosion, up-welling, ice formation, and the activities of organisms and ecosystems (Stocker et al., 2013). Ocean chemistry is also changing with global temperature, with impacts projected at 1.5°C and, more so, at 2°C (*high agreement, medium evidence*). Projected changes in the upper layers of the ocean include changes to pH, carbonate ion and oxygen content. Despite its many component processes, ocean chemistry has been relatively stable for long periods of time prior to the Industrial Period (Hönisch et al., 2012). Ocean chemistry is changing under the influence of human activities and rising greenhouse gases (*virtually certain*, Rhein et al., 2013; Stocker et al., 2013). About 30% of CO_2 emitted by human activities, for example, has been absorbed by the ocean where it has combined with water to produce a dilute acid that dissociates and drives ocean acidification (Cao et al., 2007; Stocker et al., 2013). Ocean pH has decreased by 0.1 pH units since the Pre-Industrial Period, which is unprecedented in the last 65 Ma (*high confidence*, Ridgwell and Schmidt, 2010) or even 300 Ma of Earth history (*medium confidence*, Hönisch et al., 2012).

Ocean acidification is most pronounced where temperatures are lowest (e.g. Polar regions) or where CO_2-rich water is brought to the ocean surface by upwelling (Feely et al., 2008). Acidification can also be influenced by effluents from natural or disturbed coastal land use (Salisbury et al., 2008), plankton blooms (Cai et al., 2011), and the atmospheric deposition of acidic materials (Omstedt et al., 2015). These sources may not be directly attributable to climate change, yet may amplify the impacts of ocean acidification (Bates and Peters, 2007; Duarte et al., 2013). Ocean acidification also influences the ionic composition of seawater by changing the organic and inorganic speciation of trace metals (e.g. 20-fold increases in free ion concentrations such as Al) which may have impacts although these are poorly understood (Stockdale et al., 2016).

Oxygen varies regionally and with depth, and is highest in Polar regions and lowest in the eastern basins of the Atlantic and Pacific Oceans, and the northern Indian Ocean (Doney et al., 2014; Karstensen et al., 2015; Schmidtko et al., 2017). Increasing surface water temperatures have reduced oxygen in the ocean by 2% since 1960 with other variables such as ocean acidification, sea level rise, precipitation, wind, and storm patterns playing roles (Schmidtko et al., 2017). Changes to ocean mixing and metabolic rates (due to increased temperature and supply of organic carbon to deep areas) has increased the frequency of 'dead zones', areas where oxygen levels no longer support oxygenic life (Diaz and Rosenberg, 2008). Drivers are complex and include both climate change and other factors (Altieri and Gedan, 2015) with increases in tropical as well as temperate regions (Altieri et al., 2017).

Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e. evaporation and inundation). Some regions (e.g. northern oceans and Arctic regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in salinity due to higher sea surface temperatures and evaporation (AR5 WGII Ch30, Durack et al., 2012). These changes in salinity (density) are also potentially driving changes to large scale patterns of water movement (Section 3.3.8)

3.3.11 Global synthesis

Table 3.2 present a summary of the assessments of global and regional climate changes and associated hazards for this chapter, based on the existing literature. For more detailed observation and attribution in ocean and cryosphere systems please refer to the upcoming IPCC Special Report on the Ocean and Cryophere in a Changing Climate (SROCC) due to be released in 2019.

Table 3.2: Summary of assessments of global and regional climate changes and associated hazards. Confidence and likehood statements are quoted from the relevant chapter text and are omitted where no assessment was made, in which case the IPCC Fifth Assessment Report (AR5) is given where available. Observed impacts and projected risks in natural and human systems. GMST: Global Mean Surface Temperature, AMOC: Atlantic Meridional Overturning Circulation, GMSL: Global Mean Sea Level.

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
GMST anomaly	GMST anomalies were 0.87°C (±0.10°C *likely* range) above pre-industrial (1850-1900) values in the 2006-2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (*high confidence*) [Chapter 1]	The observed 0.87°C GMST increase in the 2006-2015 decade compared to pre-industrial (1850-1900) conditions was mostly human-induced (*high confidence*) Human-induced warming reached about 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017 [Chapter 1]	1.5°C	2°C	0.5°C

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Temperature extremes	Overall decrease in the number of cold days and nighs and an overall increase in the number of warm days and nights at the global scale on land *(very likely)* Continental-scale increase in intensity and frequency of hot days and nights, and decrease in intensity and frequency of cold day and nights, in North America, Europe and Australia. *(very likely)* Increases in frequency or duration of warm spell lengths in large parts of Europe, Asia and Australia (*high confidence (likely)*), as well as on global scale (*medium confidence*) [Section 3.3.2]	Anthropogenic forcing has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century *(very likely)* [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights *(very likely)* Warming of temperature extremes highest over land, including nearly all inhabited regions *(high confidence)*, with increases of up to 3°C in mid-latitude warm season, and up to 4.5 in high-latitude cold season (*medium confidence*) Highest increase of frequency of unusually hot extremes in tropical regions (*medium confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights *(very likely)* Warming of temperature extremes highest over land, including nearly all inhabited regions (*high confidence*), with increases of up to 4°C in mid-latitude warm season, and up to 6°C in high-latitude cold season (*medium confidence*) Highest increase of frequency of unusually hot extremes in tropical regions (*medium confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights *(high confidence)* Global-scale increase in length of warm spells and decrease in length of cold spells *(high confidence)* Strongest increase in frequency for rarest and most extreme events (*high confidence*) Particularly large increases in hot extremes in inhabited regions (*high confidence*) [Section 3.3.2]

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present versus pre-industrial)	Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C global warming
Heavy precipitation	More areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation *(likely)* [Section 3.3.3]	Human influence contributed to global-scale tendency towards increases in the frequency, intensity and/or amount of heavy precipitation events (*medium confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged on global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged on global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Higher frequency, intensity and/or amount of heavy precipitation when averaded on global on land at 2°C versus 1.5°C (*high confidence)* Several regions are projected to experience increases in heavy precipitation at 2°C warming versus 1.5°C (*high confidence*), in particular in high-latitude and mountainous regions, as well as in Eastern Asia and Eastern North America (*medium confidence*) [Section 3.3.3]

	Observed change (recent past versus pre-industrial)	Attribution of observed change to human-induced forcing (present versus pre-industrial)	Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)	Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)	Differences between 2°C and 1.5°C global warming
Drought and dryness	*High confidence* in dryness trends in some regions, especially drying in Mediterranean region (including Southern Europe, Northern Africa and the Near-East) *Low confidence* in drought and dryness trends at global scale. [Section 3.3.4]	*Medium confidence* in attribution of drying trend in Mediterranean region *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]	*Medium confidence* of drying trends in Mediterranean region. *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]	*Medium confidence* of drying trends in Mediterranean region and South Africa. *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]	*Medium confidence* of stronger drying trends in Mediterranean region and South Africa at 2°C versus 1.5°C global warming. *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]
Runoff & river flooding	Streamflow trends mostly non-statistically significant (*high confidence)* Increase in flood frequency and extreme streamflow in some regions *(high confidence)* [Section 3.3.5]	Not assessed in this report.	Expansion of the global land area with significant increase in runoff (*medium confidence)* Increase in flood hazard in some regions *(medium confidence)* [Section 3.3.5]	Expansion of the global land area with significant increase in runoff (*medium confidence*) Increase in flood hazard in some regions (*medium confidence*) [Section 3.3.5]	Expansion of the global land area with significant increase in runoff (*medium confidence)* Expansion in the area affected by flood hazard *(medium confidence)* [Section 3.3.5]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Tropical & extra-tropical cyclones	*Low confidence* in robustness of observed changes [Section 3.3.6]	Not meaningful to assess given *low confidence* in changes, which are due to large inter-annual variability, heterogeneity of the observational record and contradictory findings regarding trends in the observational record.	*Low confidence* in manifestation of changes in storm tracks under 2ºC global warming *Limited evidence* that the global number of tropical cyclones will be less under 2°C of global warming compared to 1.5 °C of warming, but with an increase in the number of very intense cyclones (low confidence). [Section 3.3.6]		
Ocean temperature and circulation	*High confidence* in observed warming of upper ocean, with slightly lower rates than global warming Increased occurrence of marine heatwaves *(high confidence)* AMOC has been weakening over recent decades (*more likely than not*) [Sections 3.3.7]	*Limited evidence* attributing the weakening of AMOC in recent decades to anthropogenic forcing	Further increases in ocean temperatures, including more frequent marine heatwaves (*high confidence*) AMOC will weaken over 21st century and substantically so under high levels (higher than 2°C) of global warming (*very likely*)		
Sea ice	Continuing the trends reported in AR4, the annual Arctic sea ice extent decreased over the period 1979–2012. The rate of this decrease was *very likely* between 3.5 and 4.1% per decade (0.45 to 0.51 million	Anthropogenic forcings are *very likely* to have contributed to Arctic sea ice loss since 1979 AR5 Chapter 10 (Bindoff et al., 2013a)	At least one sea-ice-free Arctic summer after about 100 years of stabilized warming *(very likely)* [Section 3.3.8]	At least one sea-ice-free Arctic summer after about 10 years of stabilized warming (*very likely)* [Section 3.3.8]	Probability of sea-ice-free Arctic summer greatly reduced at 1.5°C versus 2°C global warming *(high confidence*) [Section 3.3.8]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
	km^2 per decade) AR5 Chapter 4 (Vaughan et al., 2013)		Intermediate temperature overshoot has no long-term consequences for Arctic sea-ice cover (*high confidence*) 3.3.8		
Sea level	It is *likely* that the rate of GMSL has continued to increase since the early 20th century, with estimates that range from 0.000 [–0.002 to 0.002] mm yr^{-2} to 0.013 [0.007 to 0.019] mm yr^{-2} AR5 Chapter 13 (Church et al., 2013)	It is *very likely* that there is a substantial contribution from anthropogenic forcings to the global mean sea level rise since the 1970s AR5 Chapter 10 (Bindoff et al., 2013a)	Not assessed in this report	Not assessed in this report	GMSL rise will be about 0.1 m less at 1.5°C versus 2°C global warming (*medium confidence*) [Section 3.3.9]
Ocean chemistry	Ocean acidification due to increased CO_2 has resulted in 0.1 pH unit decrease since the pre-industrial period which is unprecedented in the last 35 Ma (*high confidence*) [Section 3.3.10]	It is *very likely)* that oceanic uptake of anthropogenic CO_2 has resulted in acidification of surface waters. [Section 3.3.10]	Ocean chemistry is changing with global temperature with impacts projected at 1.5°C and, more so, at 2°C (*high agreement, medium evidence*) [Section 3.3.10]		

3.4 Observed impacts and projected risks in natural and human systems

3.4.1 Introduction

In Section 3.4, we explore the new literature and update the assessment of impacts and projected risks into the future for a large number of natural and human systems. We also explore adaptation opportunities laying the steps for reducing climate change, preparing the ground for later discussions on the opportunities to tackle both mitigation and adaptation while at the same time recognising the importance of sustainable development and reducing the inequities among people and societies facing climate change.

Working Group II (WGII) of the IPCC Fifth Assessment Report (AR5) provided an assessment of the literature for climate risk for natural and human systems across a wide range of environments, sectors and greenhouse gas scenarios, as well as for particular geographic regions (IPCC, 2014a, 2014b). The comprehensive assessment undertaken by AR5 evaluated the evidence of changes to natural systems, and the impact on human communities and industry. While impacts varied substantially between systems, sectors and regions, many changes over the past 50 years can be attributed to human driven climate change and its impacts. In particular, risks were observed by AR5 to be increasing for natural ecosystems as climate extremes increase in frequency and intensity, as well as those associated with fauna and flora shifting their biogeographical ranges to higher latitudes and altitudes, with consequences for ecosystem services and human dependence. AR5 also reported increasing evidence of changing patterns of disease, invasive species, as well as growing risks for coastal communities and industry, especially important when it comes to sea level rise and human vulnerability.

One of the strong themes that has emerged from AR5 was that previous assessments may have under-estimated how sensitive natural and human systems are to climate change. A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) has confirmed that many impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of those related to precipitation are by comparison less clear. Moreover there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016). The observed changes in human systems are increased by the loss of ecosystem services (e.g. reduced access to safe water) that are supported by biodiversity (Cramer et al., 2014). Limited research on the risks of warming of +1.5 and +2°C was conducted following AR5 for most key economic sectors and services, for livelihoods and poverty, and for rural areas. For these systems, climate is one of many drivers that result in adverse outcomes. Other factors include patterns of demographic change, socioeconomic development, trade, and tourism. Further, consequences of climate change for infrastructure, tourism, migration, crop yields, and other impacts interact with underlying vulnerabilities, such as for individuals and communities engaged in pastoralism, mountain farming, and artisanal fisheries, to affect livelihoods and poverty (Dasgupta et al., 2014).

Incomplete data and understanding of these lower end climate scenarios has increased the request for greater data and understanding of the projected risks of warming of 1.5°C, and 2°C for reference. This section explores the available literature on the projected risks, impacts and adaptation options, and is supported by additional information and background in Annex 3.1 (S3-4, S3-4-2, S3-4-4, S3-4-7, S3-4-12). A description of the main assessment methods of this chapter is given in Section 3.2.2.

3.4.2 Freshwater resources (quantity and quality)

3.4.2.1 Water availability

WGII AR5 concluded that about 80% of the world's population already suffers from serious threats to its water security as measured by indicators including water availability, water demand, and pollution (Vörösmarty et al., 2010). UNESCO (2011) concluded that climate change can alter the availability of water and threaten water security.

Although physical changes on streamflow and continental runoff that are consistent with climate change have been identified (Section 3.3.5), water scarcity in the past is still less well understood because the scarcity assessment needs to take into account various factors such as the operations of water supply infrastructure and human water use behaviour (Mehran et al., 2017), as well as incorporating green water, water quality, and environmental flow requirements (J. Liu et al., 2017). Over the past century, substantial growth in population, industrial and agricultural activities, and living standards have exacerbated water stress in many parts of the world, especially in semi-arid and arid regions such as California in the US (AghaKouchak et al., 2015; Mehran et al., 2015). Due to changes in climate and water consumption behavior, and particularly the effects of spatial distribution of population growth relative to water resources, the population under water scarcity increased from 0.24 billion (14% of global population) in the 1900s to 3.8 billion (58%) in the 2000s. In that last period (2000s), 1.1 billion people (17% of global population) mostly living in South and East Asia, North Africa and Middle East were facing high water shortage and high water stress (Kummu et al., 2016).

Over the next few decades, and for increases in global mean temperature of less than about 2ºC, the AR5 concluded that changes in population will generally have a greater effect on water resource availability than changes in climate. Climate change, however, will regionally exacerbate or offset the effects of population pressure (Jiménez Cisneros et al., 2014).

The differences in projected changes in runoff under 1.5ºC and 2ºC, particularly those that are regional, are described in Section 3.3.5. Constraining to 1.5ºC instead of 2ºC warming can mitigate the risks on water availability although socio-economic drivers could affect the availability more than the risks posed by the variation in warming levels, while the risks found in regions are not homogeneous (*medium evidence, medium agreement)* (Gerten et al., 2013; Hanasaki et al., 2013; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Karnauskas et al., 2018). Assuming a constant population in these models, Gerten et al. (2013) reveal that an additional 8% of the world population in 2000 will be exposed to new or aggravated water scarcity at 2ºC warming. This value is almost halved - with 50 % larger reliability - when warming is constrained to 1.5ºC. People inhabiting river basins particularly in the Middle East and Near East become newly exposed to chronic water scarcity even if the warming is constrained under 2ºC warming. Many regions especially in Europe, Australia and southern Africa appear to be affected at 1.5ºC if the reduction in water availability is computed for non-water scarce basins in addition to the reductions in water-scarce regions. From a contemporary population of approximately 1.3 billion exposed to water scarcity, about 3% (North America) to 9% (Europe) are prone to aggravated scarcity at 2ºC warming (Gerten et al., 2013). Under the Shared Socioeconomic Pathway (SSP)2 population scenario, about 8% of the global population are projected to experience a severe reduction in water resources under warming of 1.7ºC in 2021-2040, increasing to 14 % of the population under 2.7ºC in 2043-2071, based on either the criteria of discharge reduction >20% or >1 standard deviation (Schewe et al., 2014). Depending on the scenarios of SSP1 to 5, exposure to the increase of water scarcity in 2050 will be globally reduced by 184–270 million people at about 1.5ºC compared to the impacts at about 2ºC. However the variation between socio-economic differences is larger than the variation between warming levels (Arnell and Lloyd-Hughes, 2014).

On many small developing islands, there will be freshwater stress derived from projected aridity change, however, constraining to 1.5ºC warming can avoid a substantial fraction of water stress compared to 2ºC, especially across the Caribbean region, particularly on the island of Hispaniola (Dominican Republic and Haiti) (Karnauskas et al. (2018). Hanasaki et al. (2013) conclude that the projected range of changes in global irrigation water withdrawal (relative to the baseline of 1971-2000) with human configuration fixing non-meteorological variables at the period of about 2000 are 1.1–2.3% and 0.6–2.0% lower at 1.5ºC than at 2ºC, respectively. The same study, Hanasaki et al. (2013) reports on the importance of water use scenarios in water scarcity assessments, but neither quantitative nor qualitative information regarding water use are available. Hanasaki et al. (2013) conclude that the projected ranges of changes in global irrigation water withdrawal with human configuration fixing non-meteorological variables at about 2000 are 1.1–2.3% at about 1.5ºC, which is projected by Geophysical Fluid Dynamic Laboratory (GFDL) model (Representative Concentration Pathway (RCP)2.6 in 2071-2100 and RCP4.5 in 2011-2040), and 0.6‑2.0% at about 2ºC according to the projection using the Hadley Centre New Global Environmental Model (HadGEM) and Model for Interdisciplinary Research on Climate (MIROC) models (RCP4.5 and RCP8.5 in 2011-2040, respectively).

Comparing the impacts on hydropower production at 1.5°C and 2°C, it is found that mean gross potential increases in northern, eastern and western Europe, and decreases in southern Europe (Tobin et al., 2018; Jacob et al., 2018). The Baltic and Scandinavian countries will have the most positive impacts on production. The most negatively impacted are Greece, Spain, and Portugal, although the impacts can be reduced by limiting warming at 1.5°C (Tobin et al., 2018). It is found that, in Greece, Spain and Portugal, a warming of 2°C will decrease hydropower potential below 10%, while limiting to 1.5°C warming will keep the reduction to 5% or less. There is however, substantial uncertainty associated with these results due to a large spread between the climate models (Tobin et al., 2018).

Due to a combination of higher water temperatures and reduced summer river flows, the usable capacity of thermoelectric power plants using river water for cooling is expected to reduce in all European countries (Tobin et al., 2018; Jacob et al., 2018), with the magnitude of decreases being about 5% for 1.5°C and 10% for 2°C for most European countries (Tobin et al., 2018). Greece, Spain, and Bulgaria will have the largest reduction at 2°C (Tobin et al., 2018).

Fricko et al. (2016) assess the direct global energy sector water use across a broad range of energy system transformation pathways in order to identify the water impacts of a 2°C climate policy. This study revealed that there will be substantial divergence in water withdrawal for thermal power plant cooling under a condition in which the distribution of future cooling technology for energy generation is fixed, whereas adopting alternative cooling technologies and water resources will make the divergence considerably smaller.

3.4.2.2 Extreme hydrological events (floods and droughts)

WG II AR5 concluded that socio-economic losses from flooding since the mid-20th century have increased mainly due to greater exposure and vulnerability (*high confidence*; Jiménez Cisneros et al., 2014). There is *low confidence* due to *limited evidence*, however, that anthropogenic climate change has affected the frequency and the magnitude of floods. WGII AR5 also concluded that there is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand (Jiménez Cisneros et al., 2014).

Since the AR5, the number of studies related to river flooding and meteorological drought based on long-term observed data have been gradually increasing. There has been progress since the AR5 in identifying historical changes in streamflow and continental runoff (Section 3.3.5). As a result of population and economic growth, increased exposure of people and assets has caused more damage due to flooding. However, differences in flood risks among regions reflect the balance among the magnitude of the flood, population, their vulnerabilities, the value of assets affected by flooding, and the capacity to cope with flood risks that depend on socio-economic development conditions as well as topography and hydro-climatic conditions (Tanoue et al., 2016). The AR5 assessment concluded that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013b). However, recent publications based on observational and modeling evidence are supporting a gathering concensus that human emissions have substantially increased the probability of drought years in the Mediterranean region (Sections 3.3.4, Table 3.2).

WGII AR5 assessed that global flood risk will increase in the future partly due to climate change (*limited evidence*, *medium agreement*), with projected changes in the frequency of droughts longer than 12 months being more uncertain, because of their dependence on accumulated precipitation over long periods (Jiménez Cisneros et al., 2014).

Increases in the risks associated with runoff at global scale (*high confidence*), and in flood hazard in some regions (*high confidence*), can be expected at warming of 1.5°C level with an overall increase in the area affected by flood hazard at 2°C (*high confidence*) (see Section 3.3.5). There are studies, however, revealing that socio-economic conditions will exacerbate flood impacts more than global climate change, and the magnitude of the impacts can be larger in some region (Arnell and Lloyd-Hughes, 2014; Winsemius et al., 2016; Alfieri et al., 2017; Arnell et al., 2018; Kinoshita et al., 2018) (*limited evidence, medium agreement*). Assuming constant population sizes, countries representing 73% of the world population will experience increasing flood risk with an average of 580% increase at 4ºC compared to the impact simulated over the baseline period 1976-2005. Such impact is projected to be reduced to 100% increase at 1.5ºC and 170% at 2ºC (Alfieri et al., 2017). Alfieri et al. (2017) reveal that the largest increases in flood risks are found in U.S., Asia, and Europe in general, while decreases are found in only few countries in Eastern Europe and Africa. Alfiere et al (2017) report that the projected changes are not homogeneously distributed on the world land surface. Alfieri et al. (2018) studied the population affected by flood events in European states, specifically Central and Western Europe, and found that the population affected can be limited to 86% for 1.5ºC warming compared to 93% at 2ºC. Under the SSP2 population scenario, Arnell et al. (2018) find that 39% (range 36-46%) of impacts on populations exposed to river flood can be globally avoided at 1.5ºC compared to 2 ºC warming.

Under SSP1-5 scenario, Arnell and Lloyd-Hughes (2014) find that the number of people exposed to increased flooding in 2050 under warming of about 1.5ºC can be reduced by 26–34 million compared to those people exposed to increased flooding associated with 2ºC. Variation between socio-economic differences, however, are larger than the variation between the extent of global warming. Kinoshita et al. (2018) find that a serious increase in potential flood fatality (5.7%) is projected without any adaptation if global warming increases from 1.5ºC to 2ºC, whereas an increase in potential economic loss (0.9%) is relatively small. Nevertheless, the study indicates that socio-economic changes have a stronger contribution to the potentially increased consequences of future floods, and about a half of the increase of potential economic losses is mitigated by autonomous adaptation.

There is limited information about the global and regional projected risks posed by droughts at 1.5ºC and 2ºC. However, hazards by droughts under 1.5ºC can be reduced compared to the hazards at 2ºC (Section 3.3.4). Under constant socio-economic conditions, the population exposed to drought at 2ºC warming is projected to be larger than at 1.5ºC (Smirnov et al., 2016; Sun et al., 2017; Arnell et al., 2018; Liu et al., 2018) (*limited evidence, medium agreement*). Under the same scenario, the global mean monthly number of people expected to be exposed to extreme drought at 1.5ºC in 2021-2040 is projected to be 114.3 million people while 190.4 million people at 2ºC in 2041-2060 (Smirnov et al., 2016) . Under the SSP2 population scenario, Arnell et al. (2018) project that 39% (range 36-51%) of impacts on populations exposed to drought can be globally avoided at 1.5ºC compared to 2ºC.

Liu et al. (2018) study the changes in population exposure to severe droughts in 27 regions and around the globe for 1.5ºC and 2ºC warming using the SSP1 population scenario, compared to the baseline period of 1986-2005, and conclude that urban population exposure in most regions can be decreased at 1.5ºC (350.2±158.8 million) compared to 2ºC (410.7±213.5 million), respectively. Liu et al. (2018) also suggest that more urban populations will be exposed to severe droughts in Central Europe, Southern Europe, the Mediterranean, West Africa, East and West Asia and Southeast Asia, and the number of the affected people will escalate further in these regions at 2ºC. In the Haihe River Basin in China, the proportion of the population exposed to droughts at 1.5ºC is projected to be reduced by 30.4%, but increased by 74.8% at 2°C relative to 339.65 million people in the 1986–2005 period (Sun et al., 2017) .

Alfieri et al. (2018) estimate expected damage from flood at the European level for the baseline period (1976-2005), in which the reported annual figure is 5 billion euro of losses and reveal that relative changes of flood impacts rise with warming levels from 116% at 1.5°C to 137% at 2°C, respectively.

Kinoshita et al. (2018) study the increase of potential economic loss in SSP3 and project that the smaller loss at 1.5°C compared to at 2°C (0.9%) is marginal regardless of whether the vulnerability is fixed at the current level or not. Winsemius et al. (2016) show adaptation measures have the potential to greatly reduce present and future flood damage, by analyzing the differences in results with and without flood protection standard. They conclude that increases in flood induced economic impacts (% Gross Domestic Product, GDP) in African countries are mainly driven by climate change and Africa's growing assets become increasingly exposed to floods. And hence there is greater need for long-term and sustainable investments in adaptation in Africa.

3.4.2.3 Groundwater

WGII AR5 concluded that the detection of changes in groundwater systems, and attribution of those changes to climatic changes, are rare owing to a lack of appropriate observation wells and an overall small number of studies (Jiménez Cisneros et al., 2014).

Since AR5, the number of studies based on long-term observed data continues to be limited. The groundwater-fed lakes in north-eastern central Europe have been affected by climate and land use changes, and show a predominantly negative lake-level trend in 1999–2008 (Kaiser et al., 2014).

WGII AR5 concluded that climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (*robust evidence, high agreement*; Jiménez Cisneros et al., 2014).

In some regions, groundwater is often intensively used to supplement the excess demand, often leading to groundwater depletion. Climate change adds further pressure on water resources and exaggerates human water demands due to increasing temperatures over agricultural lands (Wada et al., 2017). Very few studies project the risks of groundwater depletion under 1.5ºC and 2ºC warming. Under 2ºC warming, impacts posed on groundwater are projected to be greater than at 1.5ºC (*limited evidence, low agreement*; Portmann et al., 2013; Salem et al., 2017).

Portmann et al. (2013) indicate that 2.0% (range 1.1-2.6%) of global land area is projected to suffer from an extreme decrease of renewable groundwater resources of more than 70% at 2ºC, which is clearly mitigated at 1.5ºC. The study also projects that 20% of global land surface is affected by more than 10% groundwater reduction at 1.5ºC with the percentage of the land impacted increasing at 2ºC. In a groundwater-dependent irrigated region in Northwest Bangladesh, the average groundwater level during the major irrigation period (January-April) is projected to decrease in accordance with temperature rise (Salem et al., 2017).

3.4.2.4 Water quality

WGII AR5 concluded that most observed changes to water quality from climate change are from isolated studies, mostly of rivers or lakes in high-income countries, using a small number of variables (Jiménez Cisneros et al., 2014). The AR5 report assessed that climate change is projected to reduce raw water quality, posing risks to drinking water quality with conventional treatment (*medium evidence, high agreement*; Jiménez Cisneros et al. (2014).

Since AR5, studies have detected climate change impacts on several indices of water quality in lakes, watershed and regional (e.g., Patiño et al., 2014; Aguilera et al., 2015; Watts et al., 2015; Marszelewski and Pius, 2016; Capo et al., 2017). Since WGII AR5, the number of studies utilizing RCP scenarios at regional or watershed scale have been gradually increased (e.g., Boehlert et al., 2015; Teshager et al., 2016; Marcinkowski et al., 2017). There are, however, few studies that explore projected impacts on water quality under 1.5ºC versus 2ºC warming. Differences in impacts on water quality between 1.5ºC and 2ºC warming is unclear (Bonte and Zwolsman, 2010; Hosseini et al., 2017) (*limited evidence, low agreement*). The daily probability of exceeding the chloride standard for drinking water taken from Lake IJsselmeer (Andijk, the Netherlands) is projected to increase about five times at 2ºC relative to 1ºC since 1990 (Bonte and Zwolsman, 2010). Mean monthly dissolved oxygen concentrations and nutrient concentrations in the upper Qu'Appelle River (Canada) in 2050-2055 are projected to decrease less at about 1.5ºC warming (RCP2.6 in 2050-2055) compared to about 2ºC (RCP4.5 in 2050-2055) (Hosseini et al., 2017). In the three river basins (Sekong, Sesan, and Srepok in southeast Asia) about 2ºC warming (1.05 ºC increase in the 2030s relative to the baseline peiod 1981-2008, RCP8.5), impacts posed by land-use change on water quality is projected to be greater than at 1.5ºC (0.89 ºC increase in the 2030s relative to the baseline peiod 1981-2008, RCP4.5)(Trang et al., 2017). Under the same warming scenario, Trang et al. (2017) project annual nitrogen (N) and phosphorus (P) yields change in 2030s at about 1.5ºC and about 2ºC as well as with combinations of two land-use change scenarios: 1) conversion of forest to grassland, and 2) of forest to agricultural land. The projected changes in N (P) yield under 1.5ºC and 2ºC scenarios are 7.3 (5.1)% and -6.6 (-3.6)%, whereas under the combination of land-use scenarios are 1) 5.2 (12.6)% and 8.8 (11.7)%, and 2) 7.5 (14.9)% and 3.7(8.8)%, respectively (Trang et al., 2017).

3.4.2.5 Soil erosion and sediment load

WGII AR5 concluded that there is little or no observational evidence that soil erosion and sediment load have been altered significantly due to climate change (*limited evidence, medium agreement*), (Jiménez Cisneros et al., 2014). As studies of climate change impacts on soil erosion have increased where rainfall is an important driver (Lu et al., 2013), studies have increasingly considered other factors such as rainfall intensity (e.g., Shi and Wang, 2015; Li and Fang, 2016), snow melt, and change of vegetation cover due to temperature rise (Potemkina and Potemkin, 2015), and crop management practices (Mullan et al., 2012). WGII AR5 concluded that increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices (Jiménez Cisneros et al., 2014).

While published studies of climate change impacts on soil erosion have increased since 2000 globally (Li and Fang, 2016), few articles have addressed impacts at 1.5ºC and 2ºC warming. The existing studies have found few differences in projected risks posed on sediment load under 1.5ºC and 2ºC (*limited evidence, low agreement*; Cousino et al., 2015; Shrestha et al., 2016). The differences between average annual sediment load under 1.5ºC and 2ºC warmings are not clear because of complex interactions among climate change, land cover/surface and soil management (Cousino et al., 2015; Shrestha et al., 2016). Averages of annual sediment load are projected to be similar under 1.5ºC and 2ºC , in particular in the Great Lakes region in the US as well as in the Lower Mekong region in Southeast Asia (Cousino et al., 2015; Shrestha et al., 2016).

3.4.3 Terrestrial and wetland ecosystems

3.4.3.1 Biome shifts

Latitudinal and elevational shifts of biomes (major ecosystem types) boreal, temperate, and tropical regions have been detected (Settele et al., 2014, AR5) and new studies confirm this (e.g. for shrub encroachment on tundra; Larsen et al., 2014). Attribution studies indicate that anthropogenic climate change has made a greater contribution to these changes than any other factor (Settele et al., 2014, *medium confidence*).

An ensemble of seven Dynamic Vegetation Models driven by projected climates from 19 alternative General Circulation Models (GCMs) (Warszawski et al., 2013 shows 13% (range 8-20%) of biomes transforming at 2°C warming, but only 4% (range 2-7%) doing so at 1°C; suggesting that about 7% may be transformed at 1.5°C, indicating a doubling of the areal extent of biome shifts between 1.5ºC and 2°C warming (Figure 3.15a). A single ecosystem model LPJmL (Gerten et al., 2013) illustrates that biome shifts in the Arctic, Tibet, Himalayas, South Africa and Australia would be avoided by constraining warming to 1.5°C as compared with 2°C (Figure 3.15b). Seddon et al. (2016) quantitatively identified ecologically sensitive regions to climate change in most of the continents from tundra to tropical rainforest. Biome transformation may in some cases be associated with novel climates and ecological communities (Prober et al., 2012).

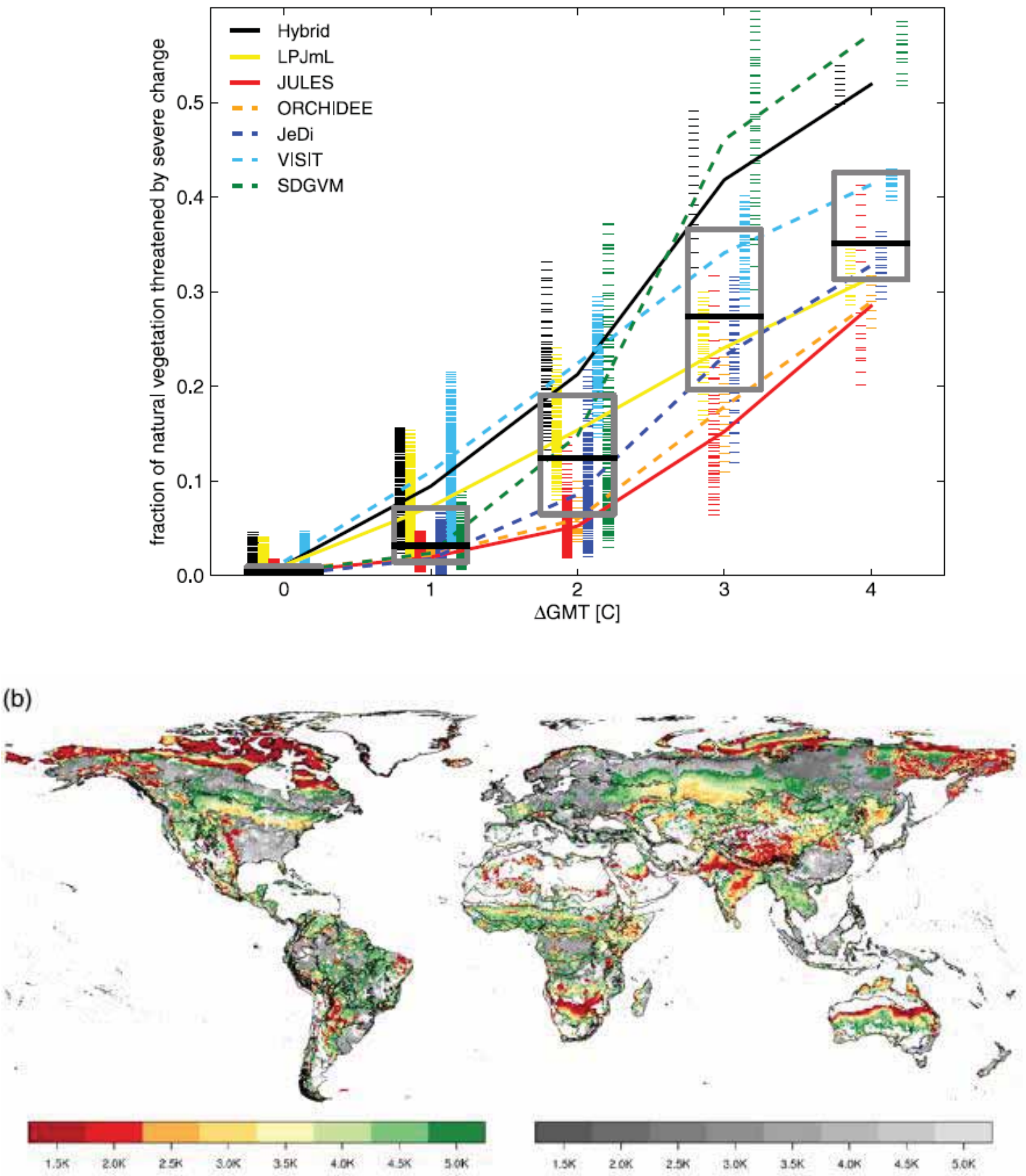


Figure 3.16: (a) Fraction of global natural vegetation (including managed forests) at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems, models, global climate change models

and Representative Concentration Pathways (RCPs). The colours represent the different ecosystem models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window centred on that year. The boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points, the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. Source: (Warszawski et al., 2013) (b) Threshold level of global temperature anomaly above pre-industrial levels that leads to significant local changes in terrestrial ecosystems. Regions with severe (coloured) or moderate (greyish) ecosystem transformation; delineation refers to the 90 biogeographic regions. All values denote changes found in >50% of the simulations. Source: (Gerten et al., 2013). Regions coloured in dark red are projected to undergo severe transformation under a global warming of 1.5°C while those coloured in light red do so at 2°C; other colors are used when there is no severe transformation unless global warming exceeds 2°C. Note: 1 K = 1ºC

3.4.3.2 *Changes in phenology*

Advancement in spring phenology of 2.8 ± 0.35 days per decade has been observed in plants and animals in most Northern Hemisphere ecosystems in recent decades (between 30°N and 72°N), and this has been attributed to changes in climate *(high confidence)* (Settele et al., 2014). The rates of change are particularly rapid in the Arctic zone in relation with higher local warming (Oberbauer et al., 2013), but in tropical forests, the phenology changes rather respond to moisture stress (Zhou et al., 2014). While a full review cannot be included here, trends consistent with this earlier finding continue to be detected, including in the flowering times of plants (Parmesan and Hanley, 2015), in the dates of egg laying and migration in birds (newly in China, Wu and Shi, 2016), in the emergence dates of butterflies (Roy et al., 2015), and in the seasonal greening-up of vegetation as detected by satellites (i.e. in the Normalised Difference Vegetation Index, NDVI, Piao et al., 2015).

The potential for de-coupling of species-species interactions due to differing phenological responses to climate change is well established (Settele et al., 2014) for example for plants and their insect pollinators (Willmer, 2012; Scaven and Rafferty, 2013). Now, mid-century projections of plant and animal phenophases in UK (Thackeray et al., 2016) clearly indicate that the timing of phenological events could change more for primary consumers (6.2 days earlier on average) than for higher trophic levels (2.5-2.9 days earlier on average), indicating the potential for phenological mismatch and associated risks for ecosystem functionality in the future, associated with global warming of 2.1-2.7°C above pre-industrial; while differing responses could alter community structure in temperate forests (Roberts et al., 2015). Here, the temperate forest phenology is projected to gain 14.3 days in the near term (2010-2039) and 24.6 days in the medium term (2040-2069), so in first approximation the difference between 2°C and 1.5°C global warming is about 10 days (Roberts et al., 2015). This phenological plasticity is not always adaptive and must be taken cautiously (Duputié et al., 2015), due to accompanying changes in climate variability (risk of frost damage for plants or earlier emergence of insects resulting in mortality during cold spells). Another adaptative response for the plants is expanding their range with increased vigor and altered herbivore resistance in their new range, analogous to invasive plants (Macel et al., 2017).

In summary, limiting warming to 1.5°C as compared with 2°C may avoid a few days of advance in spring phenology and hence decrease the risks of loss of ecosystem functionality due to phenological mismatch between trophic levels, and also of maladaptation coming from the sensitivity of many species to increased climate variability. Nevertheless, this difference between 1.5°C and 2°C warming might be limited for plants able to expand their range.

3.4.3.3 *Changes in species range, abundance and extinction*

AR5 (Settele et al., 2014) concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming: approximately 17 km per decade poleward and 11 m up in altitude per decade. Recent trends confirm this finding, for example the spatial and interspecific variance in bird populations in Europe and the North America since 1980 were found to be well-predicted by trends in climate suitability (Stephens et al., 2016). Further, a recent meta-analysis of 27 studies concerning a total of 976 species (Wiens, 2016) found that 47% of local extinctions (extirpations) reported across the globe during the 20th century could be attributed to climate change, is significantly higher in tropical regions, for animals and in freshwater habitats. IUCN (2017) lists 305 terrestrial animal and plant species from Pacific island developing nations as being threatened by climate change and severe weather. Due to lags in the responses of some species to climate change, shifts in insect pollinator ranges may result in novel assemblages with unknown implications for biodiversity and ecosystem function (Rafferty, 2017).

Warren et al. (2013) simulated climatically determined geographic range loss under 2°C and 4°C global warming for 50,000 plant and animal species accounting for uncertainty in climate projections and for the potential ability of species to disperse naturally in an attempt to track their geographically shifting climate envelope. This earlier study has now been updated and expanded to incorporate 105,501 species, including 19,848 insects, and finds that a warming of 2°C by 2100 would lead to projected bioclimatic range losses of >50% in 18 (6-35)% of 19,848 insects species, 8 (4-16)% of 12,429 vertebrate species, and 16 (9-28)% of 73,224 plant species studied (Warren et al., 2018b). At 1.5°C this falls to 6 (1-18) % insects, 4 (2-9)% vertebrates and 8 (4-15)% plants. Hence the number of insect species projected to lose over half their geographic range is reduced by two-thirds when warming is limited to 1.5°C as compared with 2°C, while the number of vertebrate and plant species projected to lose over half their geographic range is halved (Warren et al., 2018b). This is consistent with estimates made from an earlier study suggesting that range losses at 1.5°C were significantly lower for plants than those at 2°C warming (Smith et al., 2018). It should be noted that at 1.5°C warming, and if species' ability to disperse naturally to track their preferred climate geographically is inhibited by natural or anthropogenic obstacles, there still remain 10% amphibians, 8% reptiles, 6% mammals, 5% birds, 10% insects and 8% plants which are projected to lose over half their range, while species on average lose 20-27% of their range (Warren et al., 2018b). Since bird and mammal species can disperse more easily, a small proportion can gain range as climate changes, but even at 1.5°C warming the total range loss integrated over all birds and mammals greatly exceeds the integrated range gain (Warren et al., 2018b).

A number of caveats are noted in studies projecting climatic range change, since the approach does not incorporate the effects of extreme weather events and the role of interactions between species; and trophic interactions may locally counteract range expansion of species towards higher altitudes (Bråthen et al., 2018). Also, there is the potential for highly invasive species to become established in new areas as the climate changes (Murphy and Romanuk, 2014), but there is no literature that quantifies this potential for 1.5°C warming.

Pecl et al. (2017) summarize at the global level the consequences (for economic development, livelihoods, food security, human health and culture) of climate-change induced species redistribution and conclude that, even if anthropogenic greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate-driven species redistribution will be far reaching and extensive. For example, key insect crop pollinator families (Apidae, Syrphidae and Calliphoridae; i.e., bees, hoverflies and blowflies) are shown to retain significantly greater geographic ranges under 1.5°C global warming as compared with 2°C (Warren et al., 2018b). In some cases when species (such as pest and disease species) move into areas which become newly climatically suitable they may become invasive or harmful to human or natural systems (Settele et al., 2014). Some studies are beginning to locate 'refugial' areas where the climate remains suitable in the future for most of the species currently present: for example, (Smith et al., 2018) estimate that 5.5-14% more of the globe's terrestrial land area can act as climatic refugia for plants under 1.5°C warming as compared to 2°C.

There is no literature that directly estimates the proportion of species at increased risk of global (as opposed to local) commitment to extinction as a result of climate change as this is difficult to quantify. However, it is possible to compare the proportions of species at risk of very high range loss in Figure 2 in Warren et al. (2018b) where discernibly lower number of terrestrial species projected to lose over 90% of their range at 1.5°C global warming as compared with 2°C; a link between very high levels of range loss and greatly increased extinction risk may be inferred (Urban, 2015). Hence limiting global warming to 1.5°C as compared with 2°C would be expected to reduce both range losses and associated extinction risks in terrestrial species (*medium confidence*).

3.4.3.4 *Changes in ecosystem function, biomass and carbon stocks*

WGII AR5 (Settele et al., 2014) concluded that there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era and that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, yet there is no clear, consistent signal of a climate change contribution. In the northern latitudes, the productivity change has a lower velocity than the warming possibly because of lack of resource and vegetation acclimation mechanisms (M. Huang et al., 2017). Biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*), but are vulnerable to loss to the atmosphere as a result of projected increases in the intensity of storms, wildfires, land degradation and pest outbreaks (Settele et al., 2014; Seidl et al., 2017). This would contribute to a decrease in the terrestrial carbon sink. Anderegg et al. (2015) show that the total ecosystem respiration, at the global scale, has increased in response to increase of nighttime temperature (1 PgC year^{-1} °C^{-1}, p=0.02).

The increase of total ecosystem respiration in spring and autumn, in relation with higher temperature, may turn boreal forest from carbon sink to carbon source (Hadden and Grelle, 2016). This is confirmed for the boreal peatlands where increased temperature may diminish the carbon storage and compromise the stability of the peatland (Dieleman et al., 2016). In addition, J. Yang et al. (2015) showed that fires reduce carbon sink of global terrestrial ecosystems by 0.57 PgC yr^{-1} in ecosystems with high carbon storage, such as peatlands and tropical forests. Consequently for adaptation purposes, it is necessary to enhance carbon sinks, especially in forests which are prime regulators within the water, energy and carbon cycles (Ellison et al., 2017). Soil is also a key compartment for carbon sequestration (Lal, 2014; Minasny et al., 2017) depending on the net biome productivity and the soil quality (Bispo et al., 2017).

The AR5 assessed that there remains large uncertainty in the land carbon cycle behavior in the future (Ciais et al., 2013), with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all four RCP scenarios (Jones et al., 2013). Disagreement between models outweighs differences between scenarios even up to 2100 (Hewitt et al., 2016; Lovenduski and Bonan, 2017). Increased CO_2 will drive further increases in land carbon sink (Ciais et al., 2013; Schimel et al., 2015) which could persist for centuries(Pugh et al., 2016). Nitrogen, phosphorus and other nutrients, will limit terrestrial carbon cycle response to both CO_2 and climate (Goll et al., 2012; Yang et al., 2014; Wieder et al., 2015; Zaehle et al., 2015; Ellsworth et al., 2017). Climate change may accelerate plant uptake of carbon (Gang et al., 2015), but also decomposition processes (Todd-Brown et al., 2014; Koven et al., 2015; Crowther et al., 2016). Ahlström et al. (2012) found a net loss of carbon in extra-tropics and largest spread across model results in the tropics. The net effect of climate change is to reduce the carbon sink expected under CO_2 increase alone (Settele et al., 2014). Friend et al. (2014) found substantial uptake of carbon by vegetation under future scenarios when considering the effects of both climate change and elevated CO_2.

There is little published literature examining modelled land carbon changes specifically under 1.5°C warming, but here existing CMIP5 models and published data are used to draw some conclusions. For systems with significant inertia, such as vegetation or soil carbon stores, changes in carbon storage will depend on the rate of change of forcing and so are dependent on the choice of scenario (Jones et al., 2009; Ciais et al., 2013; Sihi et al., 2017). To avoid legacy effects of the choice of scenario we focus on the response of Gross Primary Productivity (GPP) – the rate of photosynthetic carbon uptake – by the models, rather than by changes in their carbon store.

Figure 3.16 shows different responses of the terrestrial carbon cycle to climate change in different regions. The models show a consistent response of increased GPP in temperate latitudes of approximately 2.0 GtC yr^{-1} K^{-1}. Similarly Gang et al. (2015) also projected a robust increase in Net Primary Productivity (NPP) of temperate forests, however Ahlström et al. (2012) show this could be offset or reversed by increases in decomposition. Globally, GPP increases or remains approximately unchanged in most models (Hashimoto et al., 2013). This is confirmed by Sakalli et al. (2017) for Europe using Euro-Cordex regional models under a 2°C global warming for the 2034-2063 period (storage will increase by +5% in soil and by +20% in vegetation). But using the same models, Jacob et al. (2018) showed that limiting warming to +1.5°C instead of +2°C avoids an increase in ecosystem vulnerability of 40-50%.

At the global scale, linear scaling is acceptable for net primary production, biomass burning, and surface runoff and impacts on terrestrial carbon storage will be greater at 2°C than at 1.5°C (Tanaka et al., 2017). If global CO_2 concentrations and temperatures stabilise, or peak and decline, then both land and ocean carbon sinks – which are primarily driven by the continued increase in atmospheric CO_2 – will also decline, and may even reverse (Jones et al., 2016) and so if a given amount of anthropogenic CO_2 is removed from the atmosphere, an equivalent amount of land and ocean anthropogenic CO_2 will be released to the atmosphere (Cao and Caldeira, 2010).

In conclusion**,** ecosystem respiration will increase with temperature, reducing soil carbon storage. Soil carbon storage will be larger if global warming is restricted to 1.5°C, although some of the associated changes will be countered by enhanced gross primary production due to elevated CO_2 concentration (i.e. the 'fertilization effect') and higher temperatures, especially at medium and high latitudes (*medium confidence*).

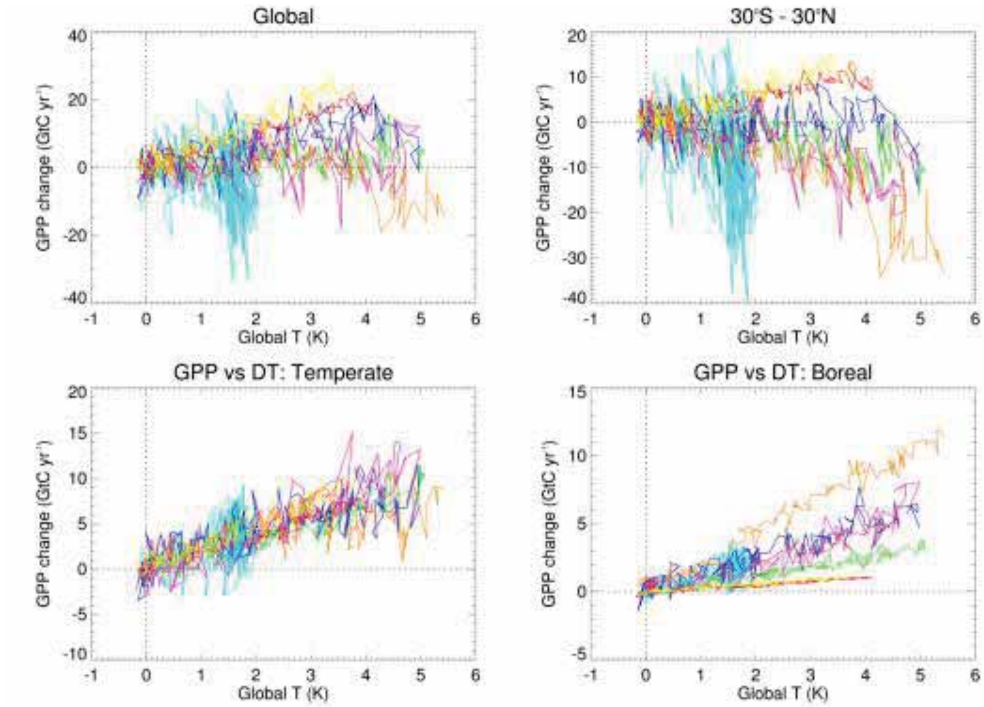


Figure 3.17: The response of terrestrial productivity (Gross Primary Productivity, GPP) to climate change, globally (top left) and for three latitudinal regions: 30°S-30°N; 30-60°N and 60-90°N. Data was used from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (http://cmip-pcmdi.llnl.gov/cmip5/). Seven Earth System Models used: Norwegian Earth System Model (NorESM-ME, yellow); Community Earth System Model (CESM, red); Institute Pierre Simon Laplace (IPLS)-CM5-LR (dark blue); Geophysical Fluid Dynamics Laboratory (GFDL, pale blue); Max Plank Institute-Earth System Model (pink); Hadley Centre New Global Environmental Model 2-Earth System (HadGEM2-ES, orange); Canadian Earth System Model 2 (CanESM2, green). Results are differences in GPP from model simulations with ('1pctCO_2') and without ('esmfixclim1') the effects of climate change. Data are plotted against global mean temperature increase above pre-industrial from simulations with 1% per year increase in CO_2 ('1pctCO_2').

3.4.3.5 Regional and ecosystem-specific risks

A large number of threatened systems including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems are assessed in the AR5. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succuluent Karoo areas of South Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, it has been shown that impacts accrue with greater warming and thus impacts at 2°C would be expected to be greater than those at 1.5°C (*medium confidence*).

The **High Arctic region**, with tundra-dominated landscapes, has warmed more than the global average over the last century (Settele et al., 2014) (Section 3.3). The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). Both of these processes facilitate conditions for the establishment of woody species in tundra areas. Arctic terrestrial ecosystems are being disrupted by delays in winter onset and mild winters associated with global warming (Cooper, 2014) (*high confidence*). Observational constraints suggest stabilisation at 1.5°C would avoid approximately 2 million km^2 of permafrost compared with stabilisation at 2°C (Chadburn et al., 2017), but the timescale for release of thawed carbon as CO_2 or CH_4 is likely to be many centuries (Burke et al., 2017). In Northern Eurasia, the growing season length is projected to lengthen by about 3-12 days for 1.5°C and 6-16 days for 2°C (*medium confidence*) (Zhou et al., 2018). Aalto et al. (2017) predict a 72% reduction of cryogenic land surface processes in Northern Europe for RCP2.6 in 2040-2069 (corresponding to a global warming of approximately 1.6°C), with only slightly larger losses for RCP4.5 (2°C global warming). Long-term absence of snow reduces vascular plant cover in the understorey by 92%, reduces fine root biomass by 39% (Blume-Werry et al., 2016)

Projected impacts on **forests** as climate changes include increases in the intensity of storms, wildfires and pest outbreaks (Settele et al., 2014), potentially leading to forest dieback (*medium confidence*). Warmer and drier conditions particularly facilitate fire, drought and insect disturbances, while warmer and wetter conditions increase disturbances from wind and pathogens (Seidl et al., 2017). Including disturbances in the simulations may influence productivity changes of European forests in response to climate change (Reyer et al., 2017b). There is additional evidence for attribution of increased forest fire in North America to anthopogenic climate change during 1984-2015, via the mechanism of increasing fuel aridity almost doubling the western US forest fire area compared to what would have been expected in the absence of climate change (Abatzoglou and Williams, 2016). This projection is in line with projected fire risks, which indicate that fire frequency would increase over 37.8% of global land areas during 2010-2039 (Moritz et al., 2012), corresponding to a global warming level of approximately 1.2 ºC; as compared with over 61.9% of the global land area in 2070-2099, corresponding to a warming of approximately 3.5ºC[2] (Table 26-1 in Romero-Lankao et al., 2014) also indicated significantly lower wildfire risks in North America for near term warming (2030-2040, which may be considered a proxy for 1.5ºC) than at 2ºC (*high confidence*).

Amazon tropical forest has been shown to be close to its climatic threshold (Hutyra et al., 2005), but this threshold may move under elevated CO_2 (Good et al., 2011). Future changes in rainfall, especially dry season length, will determine the response of Amazon forest to climate change (Good et al., 2013). The forest may be especially vulnerable to combined pressure from multiple stressors: namely changes in climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016). Modelling (Huntingford et al., 2013) and observational constraints (Cox et al., 2013) suggest large scale forest dieback less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009). Nobre et al. (2016) estimate climate threshold of 4°C and a deforestation threshold of 40%.

In many places around the world the **savanna** boundary is moving into former grasslands with woody encroachment and tree cover and biomass has increased over the past century due to changes in land management, rising CO_2, climate variability and change (often in combination) (Settele et al., 2014). For the plant species in the Mediterranean region, shift in phenology, range contraction, health decline have been observed because of precipitation decrease and temperature increase (*medium confidence*) (Settele et al., 2014). Recent studies using independent complementary approaches now show that there is a regional-scale

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[2] FOOTNOTE: The approximate temperatures are derived from (Figure 10.5 panel A, Meehl et al. 2007), which indicates an ensemble average projection of 0.7 ºC or 3ºC above 1980-1999, which is itself 0.5ºC above pre-industrial) (Figure 10.5 panel A, Meehl et al. 2007).

threshold in the Mediterranean region between 1.5 ºC and 2ºC warming (Guiot and Cramer, 2016; Schleussner et al., 2016b). Guiot and Cramer (2016) finds that only if global warming is constrained to 1.5ºC can biome shifts unprecedented in the last 10,000 years be avoided (*medium confidence*) – whilst 2ºC warming results in a decrease of 12-15% of the Mediterranean biome area. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters. It is projected to lose about 20%, 45% and 80% of its current suitable climate area under 1°C, 2°C and 3°C of global warming compared to 1961-1990, respectively (*high confidence*) (Engelbrecht and Engelbrecht, 2016). In Australia, an increase in the density of trees and shrubs at the expense of grassland species - is occurring across all major Australian ecosystems and is projected to be amplified (NCCARF, 2013). In Central America, Lyra et al. (2017) showed that with a global warming of 3°C in 2100, the tropical rainforest biomass will be reduced by more than 50% with large replacement by savanna and grassland. With a global warming close to 1.5°C in 2050, a biomass decrease 20% is projected (Lyra et al., 2017). If a linear response is assumed, with a global warming of 2°C, we deduced that the decrease may reach 30% (*medium confidence*).

Freshwater ecosystems are considered to be among the most threatened on the planet (Settele et al., 2014). Although peatlands cover only about 3% of the land surface, they hold one-third of the world's soil carbon stock (400 to 600 Pg) (Settele et al., 2014). In the Congo Basin (Dargie et al., 2017) and in the Amazonian Basin (Draper et al., 2014), the peatlands store the equivalent of the tropical forest. But this stored carbon is vulnerable to land use change and future risk of drought, for example in northeast Brazil (*high confidence*) (Figure 3.12, Section 3.3.4.2). At the global scale, they are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Magrin et al., 2014). Wetland salinization, a widespread threat to the structure and ecological functioning of inland and coastal wetlands, is occurring at a high rate and large geographic scale (Herbert et al., 2015). Settele et al. (2014) find that rising water temperatures are projected to lead to shifts in freshwater species distributions and worsen water quality. Some of these ecosystems respond non-linearly to changes in temperature, for example it has been found that the wetland function of the Prairie Pothole region in North America is projected to decline beyond a local warming of 2ºC-3ºC above present (a 1ºC local warming, corresponding to a 0.6ºC global warming) (Johnson and Poiani, 2016). If the ratio of local to global warming remains similar for these small levels of warming, this would indicate a global temperature threshold of 1.2ºC-1.8ºC warming. Hence constraining global warming to approximately 1.5ºC warming would maintain the functioning of the prairie pothole ecosystem in terms of their productivity and biodiversity, but an 20% increase of precipitation can offset a 2°C global warming (*high confidence*) (Johnson and Poiani, 2016).

3.4.3.6 Summary of implications for ecosystem services

In summary, constraining global warming to 1.5ºC rather than 2ºC has strong benefits for terrestrial wetland ecosystems and their services (*high confidence*). These benefits include avoidance of biome transformations, species range losses, increased extinction risks (all *medium confidence*), changes in phenology (*high confidence*), together with projected increases in extreme weather events which are not yet factored into these analyses (Section 3.3) all contribute to disruption of ecosystem functioning and loss of cultural, provisioning and regulating services provided by these ecosystems to humans. Examples of such services include soil conservation (avoidance of desertification), flood control, water and air purification, pollination, nutrient cycling, some sources of food, and recreation.

3.4.4 Oceans systems

The Ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate. It is also provides habitat to a large number of organisms and ecosystems that provide goods and services that are worth trillions of USD per year (e.g., Costanza et al., 2014; Hoegh-Guldberg et al., 2015). Together with local stresses (Halpern et al., 2015), climate change poses a major threat to an increasing number of ocean ecosystems (e.g. coral reefs: *virtually certain*, WGII AR5) and consequently for many coastal communities who depend on marine resources for food, livelihoods and a safe place to live. Previous sections have described changes in the ocean that include rapid increases in ocean temperature down to at least 700 m (Section 3.3.7). Anthropogenic carbon dioxide has also decreased pH, as well as affected the concentration of ions such as carbonate (Section 3.3.10 and 3.4.4.5), over a similar depth range. Increased ocean temperature has intensified storms (Section 3.3.6), as well as expanded ocean volume and increased sea levels globally (Section 3.3.9) and decreased the extent of polar summer sea ice (Section 3.3.8), as well as the overall solubility of the ocean for oxygen (Section 3.3.10). Importantly, changes in the response to climate change rarely operate in isolation. Consequently, the effect of global warming at 1.5°C versus 2°C, must be considered in the light of multiple, interactive factors that may accumulate and interact over time to produce complex risks, hazards and impacts on human and natural systems.

3.4.4.1 Observed impacts

Physical and chemical changes to the ocean from increasing atmospheric CO_2 and other GHGs are already driving significant changes to ocean systems (*very high confidence*) and will continue to do so at 1.5^{o}C and, more so, at 2^{o}C above the pre-industrial period (Section 3.3.11). These changes have been accompanied by other changes such as ocean acidification and deoxygenation (Levin and Le Bris, 2015). Risks are already significant at current greenhouse gas concentrations and temperatures, and vary significantly between depths, location and ecosystems, with impacts being singular, interactive and/or cumulative (Boyd et al., 2015).

3.4.4.2 Warming and stratification of the surface ocean

As atmospheric greenhouse gasses have increased, the global mean surface temperature (GMST) has reached about 0.87^{o}C above the pre-industrial period, and oceans have rapidly warmed from the ocean surface to the deep sea (Hughes and Narayanaswamy, 2013; Levin and Le Bris, 2015; Yasuhara and Danovaro, 2016; Sweetman et al., 2017) (*high agreement, robust evidence;* Sections 3.3.1.2 and 3.3.7). Marine organisms are already responding to these changes by shifting their biogeographical ranges to higher, relatively cooler latitudes, at rates that range from 0 to 40 km yr^{-1} (Burrows et al., 2014; Chust et al., 2014b; Bruge et al., 2016; Poloczanska et al., 2016) which has consequently affected the structure and function of the ocean, along with its biodiversity and food webs (*high agreement, robust evidence*). Movements of organisms does not necessarily equate to the movement of entire ecosystems. For example, species of reef-building corals have been observed to shift their geographic ranges yet this has not resulted in the shift of entire coral ecosystems (Woodroffe et al., 2010; Yamano et al., 2011) (*medium agreement, medium evidence*). In the case of 'less mobile' ecosystems (e.g. coral reefs, kelp forests, intertidal communities), shifts in biogeographical ranges may be limited, with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures have increased (Hoegh-Guldberg, 1999; Garrabou et al., 2009; Rivetti et al., 2014; Maynard et al., 2015; Krumhansl et al., 2016; Hughes et al., 2017b) (*high agreement, robust evidence*; see also Box 3.4). These trends will become more pronounced at 1.5^{o}C, and more so at 2^{o}C, above the preindustrial period (Hoegh-Guldberg et al., 2007; Donner, 2009; Frieler et al., 2013; Horta E Costa et al., 2014; Verges et al., 2014; Vergés et al., 2016; Zarco-Perello et al., 2017) and are *likely* to result in decreases in marine biodiversity at the equator and correspondingly increases in biodiversity at higher latitudes (Cheung et al., 2009; Burrows et al., 2014).

While the impacts of relocating species are mostly negative for human communities and industry, there are examples of short-term gains. Fisheries, for example, may expand temporarily at high latitudes in the northern hemisphere as the extent of summer sea ice recedes and NPP increases (*medium agreement, medium evidence;* Cheung et al., 2010; Lam et al., 2016; Weatherdon et al., 2016). High latitude fisheries are not only influenced by the effect of temperature on NPP but are also strongly influenced by the direct effects of changing temperatures on fish and fisheries themselves (Barange et al., 2014; Pörtner et al., 2014; Cheung et al., 2016b; Weatherdon et al., 2016; Section 3.4.4.9). Temporary gains in the productivity of high latitude fisheries are offset against a growing number of examples from low and mid latitudes where increases in sea temperature are driving decreases in NPP, due to the direct effects of elevated temperatures and/or reduced ocean mixing from reduced ocean upwelling (increased stratification; *low to medium confidence;* (Cheung et al., 2010; Ainsworth et al., 2011; Lam et al., 2012, 2014, 2016; Bopp et al., 2013; Boyd et al., 2014; Chust et al., 2014; Hoegh-Guldberg et al., 2014; Poloczanska et al., 2014; Pörtner et al., 2014; Signorini et al., 2015). Reduced ocean upwelling has implications for millions of people and industries that depend on fisheries for food and livelihoods (Bakun et al., 2015; FAO, 2016; Kämpf and Chapman, 2016) although there is *low confidence* in the projection of the size of the consequences at 1.5ºC *(low agreement, limited evidence)*. It is also important to appreciate these changes in the context of large-scale ocean processes such as the ocean carbon pump. The export of organic carbon to deeper layers of the ocean increases as NPP changes in the surface ocean, for example, with implications for food webs and oxygen levels (Boyd et al., 2014; Sydeman et al., 2014; Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015).

3.4.4.3 *Storms, inundation, and coastal run-off*

Storms, wind, waves and inundation can have highly destructive impacts on ocean and coastal ecosystems as well as the human communities that depend on them (IPCC, 2012; Seneviratne et al., 2012). The intensity of tropical cyclones across the world's ocean has increased although the overall number of tropical cyclones has decreased (Elsner et al., 2008; Holland and Bruyère, 2014) (*medium agreement, limited evidence, hence low confidence;* Section 3.3.6). The direct force of wind and waves associated with larger storms, along with changes in storm direction, increase the risks of physical damage to coastal communities as well as ecosystems such as mangroves (*medium agreement, limited evidence*; Long et al., 2016; Primavera et al., 2016; Villamayor et al., 2016; Cheal et al., 2017) and tropical coral reefs (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017). These changes are associated with increases in maximum wind speed, wave height, and the inundation, although trends in these variables vary from region to region (Section 3.3.5, Table 3.2). In some cases, this can lead to increased exposure to related impacts (reduced water quality and sediment run-off; *high agreement, medium evidence*) (Brodie et al., 2012; Wong et al., 2014; Anthony, 2016; AR5-Table 5.1).

Sea level rise also amplifies impacts from observed sea level rise (Section 3.3.9) with robust evidence that storm surge and damage are already penetrating farther inland than a few decades ago, changing conditions for coastal ecosystems and human communities, especially Small Island Developing States (SIDS, Box 3.5) and low-lying coastal communities with issues such as storm surges transforming coastal areas (Section 3.4.5; Brown et al., 2018a). Changes in the frequency of extreme events, such as more intense storms, have the potential (along with other factors such as disease, feed web changes, invasive organisms, and heat stress mortality;(Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016; Clements et al., 2017) to overwhelm the capacity for natural and human systems to recover following disturbances, as has recently been seen for centrally important ecosystems such as tropical coral reefs (Box 3.4), which have changed from coral-dominated ecosystems to asemblages dominated by other organisms such as seaweeds, with changes in associated organisms and ecosystem services (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017; Hoegh-Guldberg et al., 2017; Hughes et al., 2017a, 2017b) (*high agreement, medium evidence*). The impacts of storms are amplified by sea level rise (Section 3.4.5) with substantial challenges today and in the future for cities, delta, and small islands in particular (Section 3.4.5.2 - 3.4.5.4) as well as coastlines and ecosystems (Section 3.4.5.5 – 3.4.5.7).

3.4.4.4 Ocean circulation

The movement of water within the ocean is essential to its biology and ecology as well as the circulation of heat, water and nutrients around the planet (Section 3.3.7). The movement of these factors drives local and regional climates as well as primary productivity and food production. Firmly attributing recent changes in the strength and direction of ocean currents to climate change, however, is complicated by long-term patterns and variability (e.g., Pacific Decadal Oscillation, PDO, Signorini et al., 2015) and the lack of records that match the long-term nature of these changes in many cases (Lluch-Cota et al., 2014). An assessment of literature since the AR5 (Sydeman et al., 2014), however, has concluded that (overall) upwelling-favourable winds have intensified in the California, Benguela, and Humboldt upwelling systems, but have weakened in the Iberian system, over 60 years of records (1946-2012, Section 3.3.7) (*medium agreement, medium evidence*) and are neutral for the Canary upwelling system. These conclusions are consistent with the developing consensus that wind driving upwelling systems are likely to intensify under climate change for most systems (Sydeman et al., 2014; Bakun et al., 2015; Di Lorenzo, 2015) with potentially positive and negative consequences (Bakun et al., 2015).

Changes in ocean circulation can have profound impacts on marine ecosystems by connecting regions and facilitating the entry and establishment of species in areas where they were unknown before (e.g., 'tropicalization' of temperate ecosystems, (Wernberg et al., 2012; Verges et al., 2014; Vergés et al., 2016; Zarco-Perello et al., 2017) as well as the arrival of novel disease agents (Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016) (*medium agreement, limited evidence*). For example, the sea urchin, *Centrostephanus rodgersii*, a herbivore, has been able to reach Tasmania, where it was previously unknown, from the Australian mainland due to a strengthening of the East Australian Current (EAC; *high agreement, robust evidence*) (Ling et al., 2009). As a consequence, the distribution and abundance of kelp forests has rapidly decreased with implications for fisheries and other ecosystem services (Ling et al., 2009). These risks to marine ecosystems are likely to become greater at 1.5°C and further so at 2°C (*medium agreement, medium evidence*, Cheung et al., 2009; Pereira et al., 2010; Pinsky et al., 2013; Burrows et al., 2014).

Changes to ocean circulation can have even larger impacts in terms of scale and impacts. Weakening of the Atlantic Meridional Overturning Circulation (AMOC), for example, is projected to be highly disruptive to natural and human systems as the delivery of heat to higher latitudes via this current system is reduced. Evidence of a slowdown of AMOC has increased since AR5 (Smeed et al., 2014; Rahmstorf et al., 2015a, 2015b; Kelly et al., 2016) yet a strong causal connecton to climate change is missing (*low agreement, limited evidence*; Section 3.3.7).

3.4.4.5 Ocean acidification

Ocean chemistry encompasses a wide range of phenomena and chemical species of which many are integral to the biology and ecology of the ocean (Section 3.3.10) (Gatusso et al., 2014; Hoegh-Guldberg et al., 2014;

Pörtner et al., 2014; Gattuso et al., 2015). While changes to ocean chemistry are likely to be centrally important, the literature on how climate change might influence ocean chemistry over the short and long term is limited (*high agreement, limited evidence*). By contrast, numerous risks from the specific changes associated with ocean acidification have been identified (Dove et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015; Albright et al., 2016) with the consensus that resulting changes to the carbonate chemistry of seawater are having, and are likely to have, fundamental and substantial impacts on a wide variety of organisms and hence ecosystem processes (high agreement, robust evidence) Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a broad number of organisms and processes such as de-calcification, although some taxa that did not show the same sensitivity to changes in CO_2, pH and carbonate concentrations (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015). These risks vary with latitude (i.e. greatest changes at high latitudes) and depths, with the latter involving the rapid shoaling of the aragonite saturation horizon (i.e. where concentrations of calcium and carbonate fall below the saturation point for aragonite, a key crystalline form of calcium carbonate) as CO_2 penetrates deeper as concentrations in the atmosphere increase over time. Under many models and scenarios, the aragonite saturation reaches the surface from 2030 onwards and with poorly understood impacts and consequences for ocean organisms, ecosystems and people (Orr et al., 2005; Roberts et al., 2008; Hauri et al., 2016).

It is also difficult to reliably separate the impacts of ocean warming and acidification, especially under field settings. Ocean waters have increased in sea surface temperature (SST) by approximately 0.9°C and decreased in pH by 0.11 units since 1870-1899 ('preindustrial', Table 1 in Gattuso et al., 2015; Bopp et al., 2013). As CO_2 concentrations continue to increase along with other GHGs, pH will decrease linearly with SST, reaching 1.72°C and a decrease of 0.22 pH units (under RCP4.5) relative to the preindustrial period. These changes are likely to continue given the linear correlation of SST and pH. Experimental manipulation of CO_2, temperature and consequently acidification indicate that these impacts will continue to increase in size and scale as CO_2 and SST continue to increase in tandem (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013).

While many risks have been defined through laboratory and mesocosm experiments, there is a growing list of impacts from the field (*medium agreement, medium evidence*) that include community scale impacts on bacterial assemblages and processes (Endres et al., 2014), coccolithophores (K.L.S. Meier et al., 2014), pteropods and polar food webs (Bednaršek et al., 2012, 2014), phytoplankton (Moy et al., 2009; Riebesell et al., 2013; Richier et al., 2014), benthic ecosystems (Hall-Spencer et al., 2008; Linares et al., 2015), seagrass (Garrard et al., 2014), macroalgae (Webster et al., 2013; Ordonez et al., 2014), as well as excavating sponges, endolithic microalgae, and reef-building corals (Dove et al., 2013; Reyes-Nivia et al., 2013; Fang et al., 2014), and coral reefs (Fabricius et al., 2011; Allen et al., 2017; Box 3.4). Some ecosystems such as bathyal areas (200–3000 m) are likely to undergo significant reductions in pH by the year 2100 (0.29 to 0.37 pH units) yet evidence is currently limited despite the potential importance of these areas (Hughes and Narayanaswamy, 2013; Sweetman et al., 2017) (*medium agreement, limited evidence*).

3.4.4.6 Deoxygenation

Oxygen in the ocean is maintained by a series of processes including ocean mixing, photosynthesis, respiration and solubility (Boyd et al., 2014, 2015; Pörtner et al., 2014; Breitburg et al., 2018). Concentrations of oxygen in the ocean are declining (*high agreement, robust evidence*) due to three main factors that relate to climate change: (1) heat related stratification of the water column (less ventilation and mixing), (2) reduced oxygen solubility as ocean temperature increases, and (3) impacts of warming on biological processes that produce or consume oxygen such as photosynthesis and respiration (*high agreement, robust evidence*) (Bopp et al., 2013; Pörtner et al., 2014; Altieri and Gedan, 2015; Deutsch et al., 2015; Schmidtko et al., 2017; Shepherd et al., 2017; Breitburg et al., 2018). Similarly, a range of processes (Section 3.4.11) are also acting synergistically, including non-climate change factors such as run-off and coastal eutrophication (e.g. from coastal farming, intensive aquaculture) leading to increased phytoplankton productivity, which increase the metabolic rate of coastal microbial communities by supplying greater amounts of organic carbon (Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015). Deep sea areas are likely to experience some of the greatest challenges as abyssal seafloor habitats in areas of deep-water formation experiencing decreased water column oxygen concentrations by as much as 0.03 mL L^{-1} by 2100 (Levin and Le Bris, 2015; Sweetman et al., 2017).

The number of 'dead zones' (areas where oxygenic waters have been replaced by hypoxic conditions) has been growing strongly since the 1990s (Diaz and Rosenberg, 2008; Altieri and Gedan, 2015; Schmidtko et al., 2017). While attribution can be difficult due to the complexity of the climate and non-climate change-related processes involved, some impacts related to deoxygenation (*medium agreement, limited evidence*) include the expansion of the Oxygen Minimum Zones (OMZ) (Turner et al., 2008; Carstensen et al., 2014; Acharya and Panigrahi, 2016; Lachkar et al., 2018), physiological impacts (Pörtner et al., 2014), and mortality and/or displacement oxygenic organisms such as fish (Hamukuaya et al., 1998; Thronson and Quigg, 2008; Jacinto, 2011)and invertebrates (Hobbs and Mcdonald, 2010; Bednaršek et al., 2016; Seibel, 2016; Altieri et al., 2017). Deoxygenation interacts with ocean acidification to present substantial and combined challenges for fisheries and aquaculture (*medium agreement, medium evidence*) (Hamukuaya et al., 1998; Bakun et al., 2015; Rodrigues et al., 2015; Feely et al., 2016; S. Li et al., 2016; Asiedu et al., 2017a; Clements et al., 2017; Clements and Chopin, 2017; Breitburg et al., 2018). Deoxygenation is expected to have greater impacts as ocean warming and acidification increase (*high agreement, medium evidence*), with most impacts being larger and more numerous than today (e.g. greater challenges for aquaculture and fisheries from hypoxia), and the number of hypoxic areas continue to increase. Risks from deoxygenation are *virtually certain* to increase as warming continues although our understanding of risks at 1.5ºC versus 2ºC is incomplete (*high agreement, limited evidence*). Reducing coastal pollution and consequently the export of organic carbon into deep benthic habitats is highly likely to reduce the decline in the oxygen concentrations in coastal waters and in hypoxic areas in general (Breitburg et al., 2018).

3.4.4.7 Loss of sea ice

Sea ice has been a persistent feature of the planet's polar regions (Polyak et al., 2010) and is central to marine ecosystems, people (e.g. food, culture and livelihoods) and industries (e.g. fishing, tourism, oil and gas, and shipping). Summer sea ice in these regions (e.g. Arctic, Antarctic and Southern Ocean), however, has been retreating rapidly in recent decades (Section 3.3.8) with an assessment of the literature revealing that a fundamental transformation is occurring in polar organisms and ecosystems driven by climate change (*high agreement, robust evidence*) (Larsen et al., 2014). These changes are strongly affecting people in the Arctic who have close relationships with sea ice and associated ecosystems, and are facing major adaptation challenges as a result of sea level rise, coastal erosion, the accelerated thawing of permafrost, changing ecosystems and resources, and many other issues (Ford, 2012; Ford et al., 2015).

There is considerable and compelling evidence that a further increase of 0.5°C from today in average global surface temperature will lead to multiple levels of impact on a variety of organisms - from phytoplankton to marine mammals some of the most dramatic changes occurring in the Arctic Ocean and Western Antarctic Peninsula (Turner et al., 2014, 2017b; Steinberg et al., 2015; Piñones and Fedorov, 2016).

The impacts of climate change on sea ice is part of the focus of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), due to be released in 2019. Therefore, without intending to be comprehensive, there are a range of responses to the loss of sea ice that are occurring and are likely to increase at 1.5°C and 2°C of global warming. Photosynthetic communities such macroalgae, phytoplankton, and microalgae dwelling on the underside of floating sea ice are changing due to increased temperatures, light, and nutrient levels. As sea ice retreats, mixing of the water column increases, and phototrophs have increased access to seasonally high levels of solar radiation (Dalpadado et al., 2014; W.N. Meier et al., 2014) (*medium agreement, medium evidence*). These changes are *very likely* to stimulate fisheries productivity in high latitude regions by mid-century (Cheung et al., 2009, 2010, 2016b; Lam et al., 2014), with evidence of this is already happening for several fisheries species in high latitude regions in the northern hemisphere such as the Bering Sea, although these 'positive' impacts may be relatively short-lived (Hollowed and Sundby, 2014; Sundby et al., 2016). In addition to the impact of climate change on fisheries via impacts on NPP, there are also direct effects of temperature on fish, which may have a range of impacts (Pörtner et al., 2014). Sea ice in Antarctica is undergoing changes that exceed those seen in the Arctic (Maksym et al., 2011; Reid et al., 2015) with increases in sea ice coverage in the western Ross Sea being accompanied by strong decreases in the Bellingshausen and Amundsen seas (Hobbs et al., 2016). While Antarctica is not permanently populated, the ramifications of changes to the productivity of vaste regions such as the Southern Ocean have substantial implications as far as ocean foodwebs and fisheries are concerned.

3.4.4.8 Sea level rise

Mean sea level is increasing (Section 3.3.9) with substantial impacts already being felt by coastal ecosystems and communities (*high agreement, robust evidence*). These changes are interacting with other factors such as larger indundation and storms, which may drive greater storm surge, infrastructure damage, erosion and habitat loss (Church et al., 2013; Stocker et al., 2013; Blankespoor et al., 2014). Coastal wetland ecosystems such as mangroves, sea grasses and salt marshes are under pressure from rising sea level (*medium agreement, medium evidence*, Section 3.4.5) (Di Nitto et al., 2014; Ellison, 2014; Lovelock et al., 2015; Mills et al., 2016; Nicholls et al., 2018) as well as a wide range of other non-climate change related risks and impacts, with on-going loss of wetlands recently estimated at approximately 1% per annum across a large number of countries (Blankespoor et al., 2014; Alongi, 2015). While some ecosystems (e.g. mangroves) may be able to shift shoreward as sea levels increase, coastal development (e.g. coastal building, seawalls, and agriculture) can often interrupt shoreward shifts as does reduced sediment supplies down some rivers due to coastal development (Di Nitto et al., 2014; Lovelock et al., 2015; Mills et al., 2016).

The response to sea level rise challenges for ocean and coastal systems include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development, reduced sediment supply, and unsustainable aquaculture/agriculture in order to build ecological resilience (Hossain et al., 2015; Sutton-Grier and Moore, 2016; Asiedu et al., 2017a). Available literature largely concludes that these challenges will intensify under a 1.5°C world but will be higher at 2°C, especially when considered in the context of changes occuring beyond the end of the current century. In some cases, restoration of coastal habitats and ecosystems may be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, intensifying storms, coastal inundation, and salinization (Section 3.4.5, Box 3.5) (Arkema et al., 2013) although limits of these strategies have been identified (e.g., Lovelock et al., 2015; Weatherdon et al., 2016). These and other issues and options are explored in Section 3.4.5.

3.4.4.9 *Projected risks and adaptation options for a global warming of 1.5ºC and 2ºC above pre-industrial levels*

Given the space available, it is impossible to be comprehensive, and hence the intention here is to illustrate key risks and adaptation options in the case of the ocean using a number of key examples. This assessment builds on the recent expert consensus of Gattuso and colleagues (Gattuso et al., 2015) by assessing new literature (from 2015-2017) and adjusting the levels of risk in the light of this recent literature. To do this, we use input from the original expert group's assessment (Annex 3.1, S3-4-4) and focus particularly on the implications of global warming of 1.5ºC as compared to 2ºC. A discussion of potential adaptation options is also provided, the details of which will be further explored in later chapters of this special report. This section refers heavily to the review, analysis and literature presented in the Annex 3.1 that accompanies this report.

3.4.4.10 *Framework organisms (tropical corals, mangroves and seagrass)*

Marine organisms ('ecosystem engineers'), such as seagrass, kelp, oysters, salt marsh species, mangrove and corals, build physical structures or frameworks (i.e. sea grass meadows, kelp forests, oyster reefs, salt marshes, mangrove forests and coral reefs) which form the habitat for large numbers of species (Gutiérrez et al., 2012). These organisms in turn provide food, livelihoods, cultural significance, and services such as coastal protection (Bell et al., 2011, 2017; Cinner et al., 2012; Arkema et al., 2013; Nurse et al., 2014; Wong et al., 2014; Barbier, 2015; Bell and Taylor, 2015; Hoegh-Guldberg et al., 2015; Mycoo, 2017; Pecl et al., 2017).

Risks of climate change impacts for seagrass and mangrove ecosystems have recently been assessed by an expert group led by Short et al. (2016). Impacts of climate change were similar across a range of submerged and emerged plants. Submerged plants such as seagrass were affected mostly by temperature extremes (Arias-Ortiz et al., 2018) and indirectly by turbidity, while emergent communities such as mangroves and salt marshes were most susceptible to sea level variability and temperature extremes, which is consistent with other evidence (Di Nitto et al., 2014; Sierra-Correa and Cantera Kintz, 2015; Osorio et al., 2016; Sasmito et al., 2016), especially in the context of human activities that reduce sediment supply (Lovelock et al., 2015) or interrupt the shoreward movement of mangroves by coastal infrastructure leading to 'coastal squeeze' where coastal ecosystems are trapped between changing ocean conditions and coastal infrastructure (Mills et al., 2016). Projection of the future distribution of seagrasses suggest a poleward shift, with concern that low latitude seagrass communities may contract due to increasing stress levels (Valle et al., 2014).

Present-day risks from climate change (i.e. sea level rise, heat stress, storms and inundation) are medium for seagrass and *high* for reef building corals (Figure 3.20, Annex 3.1 S3-4-4) with evidence of strengthening of concern since the AR5 and the conclusion that tropical corals may be even more vulnerable to climate change than indicated in assessments done in 2014 (Hoegh-Guldberg et al., 2014; Gattuso et al., 2015). The current assessment also took into account the heat wave-related loss of 50% of shallow water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef. These large-scale impacts plus the observation of back-to-back bleaching events on the Great Barrier Reef predicted two decades ago (Hoegh-Guldberg, 1999) and arriving sooner than predicted (Hughes et al., 2017b, 2018), suggest that the research community has under-estimated climate risks for coral reefs. General assessment of climate risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than climate change (Alongi, 2008; Hoegh-Guldberg et al., 2014; Gattuso et al., 2015) Recent climate related die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that climate change risks may have been underestimated for mangroves as well.

With the events of the last past 3 years in mind, risks are now considered to be undetectable to moderate (i.e now moderate risks start at 1.3°C as opposed to 1.8ºC, when assessed in 2015). Consequently, when average global warming reaches 1.3°C above pre-industrial period, mangroves risk from climate change will be *moderate*, while there is very *high confidence* that tropical coral reefs will experience high risks of impacts such as very frequent mass mortalities (at least while populations of corals persist). At global warming of 1.8ºC above the preindustrial period, seagrasses are projected to reach moderate to high levels of risk (e.g. sea level rise, erosion, damage from extreme temperatures, storm damage), while risks to mangroves from climate change will remain medium (e.g. risks of not keeping up with SLR; more frequent heat stress mortality) (Figure 3.17).

Tropical coral reefs will reach a *very high risk* of impact at 2ºC (Figure 3.17; Annex 3.1 3.4.4) with most available evidence suggesting that coral dominated ecosystems will be non-existent at this temperature or higher (e.g., coral abundance near zero in most locations, intensifying storms 'flattening' reefs' 3-dimensional structure; Alvarez-Filip et al., 2009) (*high agreement, robust evidence*). Impacts at this point (coupled with ocean acidification) are likely to undermine the ability of tropical coral reefs to provide habitat for the current high levels of biodiversity as well as a range of ecosystem services important for millions of people (e.g., food, livelihoods, coastal protection, cultural services) (Burke et al., 2011).

Strategies for reducing the impact of climate change on framework organisms include reducing non-climate change stresses (e.g. coastal pollution, overfishing, destructive coastal development) in order to increase ecological resilience in the face of accelerating climate change impacts (World Bank, 2013; Ellison, 2014; Anthony et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Kroon et al., 2016; O'Leary et al., 2017) as well protecting locations where organisms may be more robust (Palumbi et al., 2014), or less exposed to climate change (Bongaerts et al., 2010; van Hooidonk et al., 2013; Beyer et al., 2018). This might involve cooler areas due to upwelling or deep-water communities that experience less extreme conditions and impacts, or variable conditions that lead to more resilient organisms. Given the potential value for promoting the survival of coral communities under climate change, efforts for preventing their loss to non-climate stresses is important (Bongaerts et al., 2010; Chollett et al., 2013, 2014; Fine et al., 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015) but see (Chollett et al., 2010; Bongaerts et al., 2017; Beyer et al., 2018; Hoegh-Guldberg et al., 2018).A full understanding of the utility and feasibility of the role of refugia in reducing the loss of ecosystems has yet to be developed (*medium agreement, limited evidence*). There is also interest in *ex situ* conservation approaches involving the restoration of corals via aquaculture (Shafir et al., 2006; Rinkevich, 2014) and 'assisted evolution' to help corals adapt to changing sea temperatures (van Oppen et al., 2015, 2017), although there are numerous challenges that must be surpassed if these remedies are to be cost effective responses to preserving coral reefs under rapid climate change (Hoegh-Guldberg, 2012, 2014a; Bayraktarov et al., 2016) (*low agreement, limited evidence*).

Integrating coastal infrastructure with ecosystems dependent on mangroves, seagrasses and salt marsh such that they are able to shift shoreward as sea levels rise. Maintaining sediment supply to coastal areas will enable mangroves can keep pace with sea level rise (Shearman et al., 2013; Lovelock et al., 2015; Sasmito et al., 2016). For this reason, reducing interventions such as damming rivers may also maintain the sediment supply needed for mangrove habitat, and hence the ability of mangroves to persist without drowning as sea level increases (Lovelock et al., 2015). In addition, integrated coastal zone management should recognize the importance and economic expediency of using natural ecosystems such as mangroves and tropical coral reefs to protect coastal human communities (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Elliff and Silva, 2017). High levels of adaptation will be required to prevent impacts on food security and livelihoods in general (*medium agreement, medium evidence*). Adaptation options include developing alternative livelihoods and food sources, ecosystem-based management/adaptation such as ecosystem restoration, and constructing coastal infrastructure that reduces the impacts of rising seas and intensifying storms (Rinkevich, 2015; Weatherdon et al., 2016; Asiedu et al., 2017a; Feller et al., 2017). Clearly, these options need to be carefully assessed in terms of feasibility, cost and scalability, as well as in the light of the coastal ecosystems involved (Bayraktarov et al., 2016).

3.4.4.11 Ocean food webs (pteropods, bivalves, krill, and fin fish)

Ocean food webs represent vast interconnected systems that transfer of solar energy and nutrients from phytoplankton to higher trophic levels (including apex predators) as well as through other food web interactions. Here, we take four representative types of marine organisms which are important within food webs across the ocean, and which illustrate the impacts and ramifications of 1.5°C and 2°C warming.

Pteropods are small pelagic molluscs that produce a calcium carbonate shell and which are highly abundant in temperate and polar waters, where they form an important link in the food web between phytoplankton and a range of other organisms including fish, whales and birds. The second group, bivalve molluscs (e.g. clams, oysters and mussels) are also filter-feeding invertebrates that underpin important fisheries and aquaculture industries (from the polar to tropical regions) and are important as food sources for a range of organisms including humans. The third group of organisms considered here are a globally significant group of invertebrates known as euphausiid crustaceans (krill), and which are a key food source for many marine organisms and hence a major link between primary producers and higher trophic levels (e.g. fish, mammals, sea birds). Antarctic krill, *Euphausia superba*, are among the most abundant species in mass and are consequently an essential component of polar food webs (Atkinson et al., 2009). The last group, the fin fishes, are vitally important components of ocean food webs, and contribute to the income of coastal communities, industries and nations, and are important to food security and livelihoods of hundreds of millions of people globally (FAO, 2016). Further background to this section is provided in Annex 3.1 (S3-4-4).

There is a moderate risk to ocean food webs under present day conditions (Figure 3.17, *medium to high confidence*). Changing water chemistry and temperature is affecting the ability of pteropods to produce their shells, as well as swim and survive (Roberts et al., 2008; Bednaršek et al., 2016). Shell dissolution is 19-26% higher, for example, in both nearshore and offshore populations since the pre-industrial period (Feely et al., 2016). There is considerable concern as to whether these organisms are declining further, especially given their central importance in ocean food webs (David et al., 2017). Reviewing the literature reveals that pteropods face high risks of impact at 1.5°C and increasing risks of impacts at average global temperatures of 2°C or more above the preindustrial period (*medium agreement, medium evidence*).

As temperatures increase to 1.5°C and beyond, the risk of impacts from ocean warming and acidification remain moderate to high except in the case of bivalves (mid latitude) where the risks of impacts become high to very high. Ocean warming and acidification are already affecting the life history stages of bivalve molluscs (e.g., Asplund et al., 2014; Mackenzie et al., 2014; Waldbusser et al., 2014; Zittier et al., 2015; Shi et al., 2016; Velez et al., 2016; Q. Wang et al., 2016; Castillo et al., 2017; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017). Impacts on adult bivalves include decreased growth, increased respiration, and reduced calcification with larval stages tending to show greater developmental abnormalities and mortality after exposure (Q. Wang et al., 2016; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017) (*medium agreement, robust evidence*). Risks accumulate at higher temperatures for bivalve molluscs, with very high risks at 1.8°C or more. This general pattern continues with low latitude fin fish acquiring medium to high risks of impact (*medium agreement, medium evidence)* when average global surface temperatures reach 1.3°C above the pre-industrial period, and very high risks at 1.8°C (Figure 3.17; *medium agreement, medium evidence*).

Large scale changes to food web structure is occurring in all oceans. For example, record levels of sea ice loss in the Antarctic (Notz and Stroeve, 2016; Turner et al., 2017b) translate as a loss of habitat and hence abundance of krill (Piñones and Fedorov, 2016), with negative ramifications for seabirds and whales which feed on krill (Croxall, 1992; Trathan and Hill, 2016). Other influences such as high rates of ocean acidification, coupled with the shoaling of the aragonite saturation horizon, are likely to also play key roles (Kawaguchi et al., 2013; Piñones and Fedorov, 2016). As with many risks associated with impacts at the ecosystem scale, most adaptation options focus on the management of non-climate change stresses from human activities. Reducing non-climate change stresses such as pollution and habitat destruction will be important in efforts to maintain these important food web components. Fisheries management (especially for low latitude fin fisheries that include small scale fisheries) at local to regional scales will be important in reducing stress on food web organisms such as those discussed here, as well as helping communities and industries adapt to changing food web structure and resources (see further discussion of fisheries *per se* below; Section 3.4.6.3). One strategy might be to maintain higher population levels of fished species in order to provide more resilient stocks in the face of challenges driven by climate change (Green et al., 2014; Bell and Taylor, 2015).

3.4.4.12 Key ecosystem services (e.g. carbon uptake, coastal protection, and tropical coral reef recreation)

The ocean provides important services that include the regulation of atmospheric composition via gas exchange across the boundary between ocean and atmosphere, and storage of carbon in vegetation and soils associated with ecosystems such as mangroves, salt marsh, and coastal peatlands, among other components. These include a series of physicochemical processes which are influenced by ocean chemistry, circulation, oceanography, temperature and biogeochemical components, as well as by non-climate activities (Boyd, 2015). The ocean is also a net sink for CO_2 (another important service), absorbing approximately 30% of human emissions from the burning of fossil fuels and modification of land use (IPCC, 2013).

Carbon uptake by the ocean is decreasing (Iida et al., 2015), with risks becoming high as 2°C is approached and prospects of undersaturation of the ocean carbonate system increase (especially for polar oceans; Bopp et al. 2013). Concern is also growing from observations and models regarding changes in ocean circulation (Rahmstorf et al., 2015b); Sections 3.3.7 and 3.4.4.4). Biological components of carbon uptake by the ocean are also changing with observations of changing NPP in equatorial (*medium agreement, medium evidence*) and coastal upwelling systems (*medium agreement, medium evidence*) (Lluch-Cota et al., 2014; Sydeman et al., 2014; Bakun et al., 2015) as well as subtropical gyre systems (Signorini et al., 2015, *low agreement, limited evidence*). There is general agreement that NPP will decline as ocean warming and acidification increase (Bopp et al., 2013; Boyd et al., 2014; Pörtner et al., 2014; Boyd, 2015) (*medium agreement, medium evidence*).

Risks of impacts from reduced carbon uptake, coastal protection, and services contributing to coral reef recreation are moderate at 1.5˚C of warming (*medium agreement, limited evidence*). At 2˚C, risks of impacts associated with changes to carbon uptake remain moderate, while the climate risks associated with reduced coastal protection and recreation on tropical coral reefs are high, especially given the vulnerability of this ecosystem and others (e.g. seagrass, mangroves) to climate change (Figure 3.17). Coastal protection is another service provided by natural barriers such as mangroves, seagrass meadows, coral reefs, and other coastal ecosystems, and which is important for protecting human communities and infrastructure against the impacts associated with rising sea levels, waves and intensifying storms (Gutiérrez et al., 2012; Kennedy et al., 2013; Ferrario et al., 2014; Barbier, 2015; Cooper et al., 2016; Hauer et al., 2016; Narayan et al., 2016). Both natural and human coastal protection have the potential to reduce impacts (Fu and Song, 2017). Tropical coral reefs, for example, provide effective protection by dissipating about 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al., 2014; Narayan et al., 2016). Mangroves play an important role in coastal protection as well as resources for coastal communities but are already under moderate risk of not keeping up with the sea level rise due to climate change and to contributing factors such as reduced sediment supply or obstacles for the shift shoreward (Saunders et al., 2014; Lovelock et al., 2015). This implies that coastal areas currently protected by mangroves may experience growing risks over time.

Tourism is one of the largest industries globally (Rosselló-Nadal, 2014; Markham et al., 2016; Spalding et al., 2017). A substantial part of the global tourist industry is associated with tropical coastal regions and islands where tropical coral reefs and related ecosystems play important roles (Section 3.4.9.1). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly SIDS (Section 3.4.9.1., Box 3.5; Weatherdon et al., 2016; Spalding et al., 2017). The direct relationship between increasing global temperatures, intensifying storms, elevated thermal stress, and the loss of tropical coral reefs has raised concern about the risks of climate change for local economies and industries based on tropical coral reefs. Risks to coral reef recreational services from climate change are considered here as well as in Box 3.5, Section 3.4.9, and Annex 3.1 S3-4-4.

Adapting to the broad global changes in carbon uptake by the ocean are limited and are discussed with respect to the changes in NPP and their implications for fishing industries later in this report. These are broad scale and indirect, with the only other solution at scale being reducing the entry of CO_2 into the ocean. Strategies for adapting to reduced coastal protection involve avoidance of vulnerable areas, managed retreat from threatened locations, and/or accommodation of impacts and loss of services (Bell, 2012; André et al., 2016; Cooper et al., 2016; Mills et al., 2016; Raabe and Stumpf, 2016; Fu and Song, 2017) Within these broad options, there are strategies that involve direct human intervention (e.g. coastal hardening, seawalls and artificial reefs) (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016), while there are others that exploit the opportunities for increasing coastal protection by involving a naturally occurring oyster banks, coral reefs, mangroves, seagrass, and other ecosystems (UNEP-WCMC, 2006; Scyphers et al., 2011; Zhang et al., 2012; Ferrario et al., 2014; Cooper et al., 2016). Natural ecosystems, when healthy, also have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and other human responses that require constant maintenance (Barbier, 2015; Elliff and Silva, 2017). Recognizing and restoring coastal ecosystems in general may be more cost-effective than human structures such as the installation of seawalls and coastal hardening, where natural adaptation (ecosystem-based adaptation) is limited and the costs of creating and maintaining structures is generally expensive (Temmerman et al., 2013; Mycoo, 2017).

Recent studies have increasingly stressed the need for coastal protection to be considered within the context of new ways of managing coastal land, including protecting and ensuring that coastal ecosystems are able to undergo shifts in their distribution and abundance (Clausen and Clausen, 2014; Martínez et al., 2014; Cui et al., 2015; André et al., 2016; Mills et al., 2016)(André et al., 2016). Facilitating these changes will require new tools in terms of legal and financial instruments, as well as integrated planning that involves not only human communities and infrastructure, but also associated ecosystem responses and values (Bell, 2012; Mills et al., 2016). In this regard, the interactions between climate change, sea level rise and coastal disasters are being increasingly informed by models (Bosello and De Cian, 2014) with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al., 2016). Adaptation options for tropical coral reef recreation include: (1) Protecting and improving biodiversity and ecological function by minimizing the impact of non-climate change stresses (e.g. pollution, overfishing), (2) Ensuring adequate levels of coastal protection by supporting and repairing ecosystems that protect coastal regions, (3) ensuring fair and equitable access to the economic opportunities associated with recreational activities, and (4) seeking and protecting supplies of water for tourism, industry, and agriculture alongside community needs.

In summary, our understanding of systems has increased significantly since AR5, with multiple lines of evidence supporting very significant changes in the structure and function of the ocean and its resident organisms and ecosystems. These changes are occurring today and will get progressively less manageable as temperatures increase to 1.5°C or higher. There is considerable evidence that avoiding 2°C will avoid very substantial damage to ecosystem services and ultimately impacts on human livelihoods, food resources, communities and industries. Figure 3.17 (and additional online material, S3-3.4.4) summarises the additional risks of impacts from global warming for many of the ocean-based organisms, ecosystems and sectors discussed here.

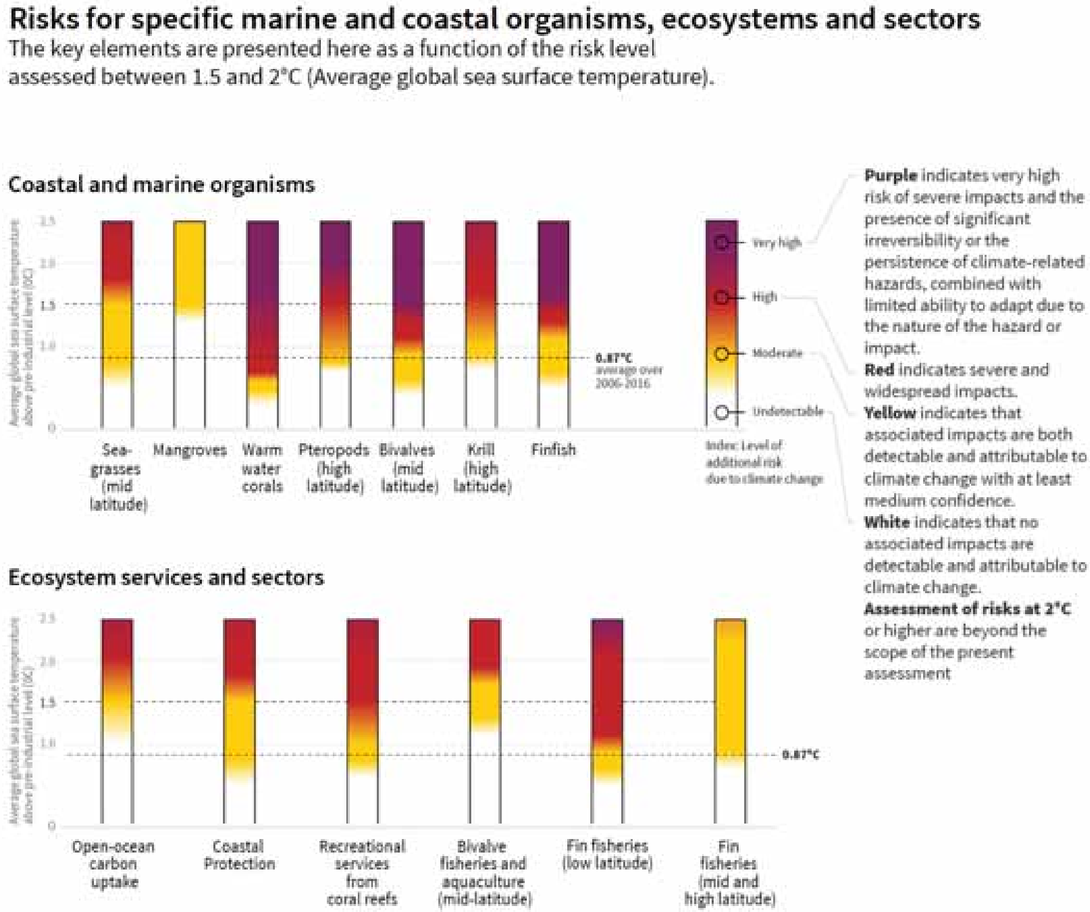

Figure 3.17: Summary of additional risks of impacts from ocean warming (and associated climate change factors such ocean acidification) for a range of ocean organisms, ecosystem and sectors at 1.0ºC, 1.5ºC and 2.0ºC warming of average sea surface temperature (SST) relative to the preindustrial period. The dotted line (0.87ºC) is a measure of the extent of present day warming. Assessment of changing risk levels and associated confidence were derived from the expert judgement of Gattuso et al., (2015) and the Lead Authors of this Chapter plus the additional input was received from the many reviewers of the ocean systems section of SR1.5. Note: (1) The analysis done here is not intended to be comprehensive. The examples of organisms, ecosystems and sectors discussed here are intended to outline the evidence and projection of impacts and the risks for ocean systems at 1.5º and 2.0ºC relative to 0.87ºC (today). (2) The evaluation of risks by experts did not consider genetic adaptation, acclimatization, or human risk reduction strategies (mitigation and societal adaptation). (3) As discussed elsewhere (3.3.10, 3.4.4.5, Box 3.4; Gattuso et al 2015), ocean acidification is also having impacts on organisms and ecosystems as carbon dioxide increases in the atmosphere. These changes are part of the response reported here although partitioning the effects of the two drivers is difficult at this point in time and hence is not attempted. (4) Confidence levels (L=Low, M=Moderate, H=High, and VH=Very high) were assessed for the position of the transitions from one level of additional climate risk to the next successive level (Gattuso et al. (2015). Three transitions were possible: W-Y (white to yellow), Y-R (yellow to red), and R-P (red to purple), with the colours corresponding to the level of additional risk posed by climate change (see Figure 3.17).

For each of the 13 Ocean 'embers', the levels of confidence for these transitions were assessed (based on level of agreement, extent of evidence) to be: Seagrasses (mid-latitude): W-Y (VH); Y-R (H); R-P(H); Mangroves: W-Y (M); Warm water corals: W-Y (H); Y-R (VH); R-P (VH); Pteropods (high latitude): W-Y (L); Y-R (M); R-P (H); Bivalves (mid-latitude): W-Y (H); Y-R (M); R-P (M), Krill (high latitude): W-Y (M); Y-R (L); R-P (L); Finfish: W-Y (H); Y-R (H); R-P (M); Open ocean carbon uptake: W-Y (H); Y-R (H); Coastal protection: W-Y (M); Y-R (L); R-P (L); Recreational services from coral reefs: W-Y (H); Y-R (M); R-P (M); Bivalve fisheries and aquaculture (mid-latitude): W-Y (H); Y-R (M); Fin fisheries (low latitude): W-Y (H); Y-R (M); R-P (H); and Fin fisheries (high latitude): W-Y (H); Y-R (H); R-P (L)

[START BOX 3.4 HERE]

Box 3.4: Tropical Coral Reefs in a 1.5ºC Warmer World

Tropical coral reefs face very high risks (Figure 3.19) of becoming unsustainable as coral dominated ecosystems if warming exceeds 1.5ºC. A 1.5°C world is better for coral reefs than a 2ºC world, in which coral reefs mostly disappear (Donner et al., 2005; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; van Hooidonk et al., 2016; Frieler et al., 2017; Hughes et al., 2017a). Even with warming up until today (0.87ºC;Chapter 1), a substantial proportion of coral reefs have experienced large scale mortalities that are causing them to rapidly contract (Hoegh-Guldberg et al., 2014). In the last 3 years alone, large coral reef systems such as the Great Barrier Reef (Australia) have lost as much as 50% of their shallow water corals (Hughes et al., 2017b). These changes are part of a series of heat stress impacts that began in the early 1980s events (Hoegh-Guldberg, 1999).

Coral dominated reefs are found between latitude 30°S and 30°N along coastlines where they provide habitat for over a million species (Reaka-Kudla, 1997). The food, income, coastal protection, cultural context, and many other services for millions of people along tropical coastal areas (Burke et al., 2011; Cinner et al., 2012; Kennedy et al., 2013; Pendleton et al., 2016) are underpinned by a mutualistic symbiosis between reef-building corals and dinoflagellates from the genus *Symbiodinium* (Hoegh-Guldberg et al., 2017). Tropical coral reefs are found down to depth of 150 m and are dependent on light, as distinct from the cold deep-water reef systems that extend down to depths of 2000 m or more. The difficulty in accessing deep-water reef systems also means that the literature on impacts of climate change is limited by comparison to tropical coral reefs (Hoegh-Guldberg et al., 2017). Consequently, this Box focuses on the impacts of climate change on tropical coral reefs, particularly with respect to their prospects under average global surface temperatures of 1.5°C and 2ºC above the pre-industrial period.

The distribution and abundance of coral reefs has decreased by approximately 50% over the past 30 years (Gardner et al., 2005; Bruno and Selig, 2007; De'ath et al., 2012) as a result of pollution, storms, overfishing and unsustainable coastal development (Burke et al., 2011; Halpern et al., 2015; Cheal et al., 2017). More recently, climate change (heat stress; Hoegh-Guldberg, 1999; Baker et al., 2008; Spalding and Brown, 2015; Hughes et al., 2017b) has emerged as the greatest threat to coral reefs with temperatures of just 1°C above the long-term summer maximum for an area (referenced to 1985-1993) over 4-6 weeks being enough to cause mass coral bleaching (loss of the symbiosis) and mortality (*very high confidence*, WGII AR5 Box 18-2, Cramer et al., 2014). Ocean warming and acidification can also slow growth and calcification, making corals less competitive to other benthic organisms such as macroalgae (Dove et al., 2013; Reyes-Nivia et al., 2013, 2014). As corals disappear, so do fish stocks, and many other reef-dependent species, directly impacting industries such as tourism and fisheries, as well as coastal livelihoods for many, often disadvantaged, people (Wilson et al., 2006; Graham, 2014; Graham et al., 2015; Cinner et al., 2016)(Pendleton et al., 2016). These impacts are exacerbated by increasingly intense storms (Section 3.3.6), which physically destroy coral communities and hence reefs (Cheal et al., 2017), and by ocean acidification (Sections 3.3.10 and 3.4.4.5) which can weaken coral skeletons, contribute to disease, and slow the recovery of coral communities after mortality events (Gardner et al., 2005; Dove et al., 2013; Kennedy et al., 2013; Webster et al., 2013; Hoegh-Guldberg, 2014b; Anthony, 2016) (*medium agreement, limited evidence*). Ocean acidification also leads to greater activity by decalcifying organisms such as excavating sponges (Kline et al., 2012; Dove et al., 2013; Fang et al., 2013, 2014, Reyes-Nivia et al., 2013, 2014).

Predictions of back-to-back bleaching events (Hoegh-Guldberg, 1999) have become reality over 2015-2017 (e.g., Hughes et al., 2017b) as have projections of declining coral abundance (*high confidence*). Models have also become increasingly capable, and predict the large-scale loss of coral reefs by mid-century under even low emission scenarios (Hoegh-Guldberg, 1999; Donner et al., 2005; Donner, 2009; van Hooidonk and Huber, 2012; Frieler et al., 2013; Hoegh-Guldberg et al., 2014; van Hooidonk et al., 2016). Even achieving emission reduction goals consistent with the ambitious goal of 1.5ºC under the Paris Agreement will result in the further loss of 90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2ºC or more above the pre-industrial period (Frieler et al., 2013; Hoegh-Guldberg, 2014b; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; Hughes et al., 2017a).

The assumptions underpinning these assessments are considered to be highly conservative. In some hypothetical cases, 'optimistic' assumptions in models include the rapid thermal adaptation by corals (0.2-1.0ºC per decade and 0.4ºC per decade; (Donner et al., 2005; Schleussner et al., 2016b), respectively) as well as very rapid recovery rates from impacts (i.e., 5 years; Schleussner et al., 2016b). Adaptation to climate change at these high rates (if at all) has not been documented and rates of recovery from mass mortality tend to be much longer the time between extreme events (> 15 years; Baker et al., 2008). Probability analysis also reveals that the underlying increases in sea temperatures that drive coral bleaching and mortality are 25% less likely under 1.5°C versus 2ºC (King et al., 2017). Differences between rates of heating suggest the possibility of temporary climate refugia (Caldeira, 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015; Keppel and Kavousi, 2015) which may play an important role in terms of the regeneration coral reefs, especially if these refuges are protected from non-climate change risks. Higher latitude sites are reporting the arrival of reef-building corals, which may deserve focus in terms of limited refugia and coral reef structures, which are likely to be low in biodiversity when compared to tropical reefs today (Kersting et al., 2017). Similar proposals have been made for the potential role of deep water (30 to 150 m) or mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016) avoiding shallow water extremes (i.e. heat, storms) although the ability of these ecosystems to repopulate damaged shallow water areas may be limited (Bongaerts et al., 2017).

Given the sensitivity of corals to heat stress, even short periods of overshoot (i.e. decades) will be very challenging to coral reefs. Losing 90% of today's coral reefs, however, will remove resources and increase poverty levels across the world's tropical coastlines, highlighting the key issue of equity for the millions of people that depend on these valuable ecosystems (Spalding et al., 2014; Halpern et al., 2015)(Cross Chapter Box 6). Anticipating these challenges to food and livelihoods for coastal communities will become increasingly important, and as will adaptation options such as the diversification of livelihoods and the development of new sustainable industries to reduce the dependency of coastal communities on threatened coastal ecosystems such as coral reefs (Cinner et al., 2012, 2016; Pendleton et al., 2016). At the same time, coastal communities will need to pre-empt changes to other services provided by coral reefs such as coastal protection (Kennedy et al., 2013; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014; Gattuso et al., 2015). Other threats and challenges to coastal living such as sea level rise will amplify challenges from declining coral reefs. Given the scale and cost of these interventions, implementing them earlier rather than later would be expedient.

[END BOX 3.4 HERE]

3.4.5 Coastal and low-lying areas, and sea level rise

Sea level rise (SLR) is accelerating in response to climate change (Section 3.3.9; Church et al., 2013) and is producing significant impacts (*high agreement, robust evidence*). In this section, impacts and projections of sea level rise are reported at global and city scales (Sections 3.4.5.1-3.4.5.2) and for coastal systems

(Sections 3.4.5.3 – 3.4.5.6). For some sectors, there is a lack of precise evidence of change at 1.5°C and 2°C. Adaptation to sea level rise is discussed in Section 3.4.5.7.

3.4.5.1 Global / sub-global scale

Sea level rise (SLR) and other oceanic climate change will result in salinization, flooding and erosion and affect human and ecological systems, including health, heritage, freshwater, biodiversity, agriculture, fisheries and other services (*very high agreement, robust evidence)*. Due to the commitment to SLR, there is an overlapping uncertainty in projections (Schleussner et al., 2016b; Sanderson et al., 2017; Goodwin et al., 2018; Mengel et al., 2018; Nicholls et al., 2018; Rasmussen et al., 2018) of about 0.1 m difference in Global Mean Sea Level (GMSL) rise between 1.5ºC and 2ºC worlds in 2100 (Section 3.3.9, Table 3.3). Exposure and impacts at 1.5°C and 2ºC differ at different time horizons (Schleussner et al., 2016b; Brown et al., 2018a, b; Nicholls et al., 2018; Rasmussen et al., 2018). However, these are distinct from higher rises in temperature (e.g., 4°C or more as discussed in Brown et al., 2018a) over centennial scales. The benefits of climate change mitigation reinforce findings of earlier IPCC reports (e.g., Wong et al., 2014).

Table 3.3 notes the land and people exposed to sea level rise (assuming there is no adaptation or protection at all) using the Dynamic Interactive Vulnerability Assessment (DIVA) model (extracted from Brown et al., 2018a) and Goodwin et al., 2018); Also see Annex 3.1, Table S4). Thus, even with temperature stabilization, exposure increases. In contrast, land area exposed is projected to at least double by 2300 using a RCP8.5 scenario (Brown et al., 2018a). In the 21st century, land area exposed to sea level rise (assuming there is no adaptation or protection at all) is at least an order of magnitude larger than the cumulative land loss due to submergence (which takes into account defences) (Brown et al., 2016, 2018a) regardless of sea level rise scenario. Slower rates of rise due to climate change mitigation may provide greater opportunity for adaptation (*medium confidence*), which can substantially reduce impacts.

Agreeing with WGII AR5 Section 5.4.3.1 (Wong et al., 2014), climate change mitigation may reduce or delay coastal impacts and exposure (*very high confidence, robust evidence*). Adaptation has the potential to substantially reduce risk (Nicholls et al., 2007; Wong et al., 2014; Sections 5.5 and 5.4.3.1; Sections 6.4.2.3 and 6.6,). At 1.5°C in 2100, 31–69 million people world-wide could be exposed to flooding assuming no adaptation or protection at all (and 2010 population values), compared with 32–79 million people at 2ºC in 2100 (Rasmussen et al., 2018) (Annex 3.1, Table S4). As a result, up to 10.4 million more people would be exposed to sea-level rise at 2°C compared with 1.5°C in 2100. With a 1.5°C stabilization scenario in 2100, 55-94 million people / year are at risk from flooding increasing to 115-188 million people per year in 2300 (50th percentile, SSP1-5, no socio-economic change after 2100). This assumes there is no upgrade to present protection levels (Nicholls et al., 2018). The number of people at risk increases by approximately 18% using a 2°C scenario and 266% using a RCP8.5 scenario in 2300 (Nicholls et al., 2018). Through prescribed IPCC Special Report on Emission Scenarios (SRES) SLR scenarios, Arnell et al. (2016) also found people flooded increased substantially after 2ºC without further adaptation from present protection levels, particularly in the second half of the twentieth century.

Coastal flooding by the sea is likely to cost thousands on billions of USD annually, with damage costs under constant protection 0.3–5.0% of global GDP in 2100 for a RCP2.6 scenario (Hinkel et al., 2014). Risks are projected to be highest in south and south-east Asia, assuming there is no upgrade to present protection levels, for all temperatures of climate warming (Arnell et al., 2016; Brown et al., 2016) Countries where at least 50 million people exposed to SLR (assuming no adaptation or protection at all) based on a 1,280 Pg C emission scenario (approximately 1.5°C temperature rise above today's level) include China, Bangladesh, Egypt, India, Indonesia, Japan, Philippines, United States and Vietnam (Clark et al., 2016). Rasmussen et al. (2018) and Brown et al. (2018a) project similar countries at high exposure from SLR. Thus there is *high confidence* that SLR will have significant impacts world-wide in this century and beyond.

3.4.5.2 Cities

Observations of the impacts of SLR are difficult to record due to multiple drivers of change in cities. Rather, there are observations of ongoing or planned adaptation to SLR and extreme water levels, and this will continue (Araos et al., 2016; Nicholls et al., 2018), whilst other cities are yet to prepare (see Section Cross-chapter Box 4.1) (*high confidence, medium to robust evidence*). There are limited observations and analysis of how cities will cope with higher and/or multi-centential SLR, with the exception of Amsterdam, New York and London (Nicholls et al., 2018).

Coastal urban areas are projected to see more exteme water levels due to rising sea levels which may lead to increased flooding and damage of infrastructure from extreme events (unless adaptation is undertaken), plus salinization of groundwater. These impacts may be enhancement through localized subsidence (Wong et al., 2014) causing greater relative SLR. At least 136 mega cities (port cities with a population greater than 1 million in 2005) are at risk from flooding due to SLR (with magnitudes of rise possible under 1.5°C or 2ºC in the 21st century, as indicated in Section 3.3.9) unless further adaptation is undertaken (Hanson et al., 2011; Hallegatte et al., 2013). Many of these cities are located in south and south-east Asia (Hallegatte et al., 2013; Cazenave and Cozannet, 2014; Clark et al., 2016; Jevrejeva et al., 2016). Jevrejeva et al. (2016) report with 2°C of warming by 2040 (for RCP8.5), more than 90% of global coastlines will experience SLR greater than 0.2 m. However, for scenarios where 2°C is stabilized or occurs later in time, this figure is likely to differ due to the commitment to SLR. Raising exisiting dikes helps to protect against SLR substantially reducing risk (whilst acknowledging other forms of adaptation exist). By 2300, dike heights under an unmitigation scenario (RCP8.5) could be more than 2 m higher (on average for 136 mega cities) than under climate change mitigation scenarios at 1.5°C or 2°C (Nicholls et al., 2018). Thus, rising sea levels commits to long-term adaptation in coastal cities. Thus, rising sea levels commits to long-term adaptation in coastal cities (*high confidence*).

3.4.5.3 Small islands

Qualitative physical observations of SLR (and other stresses) include inundation of parts of low-lying islands, land degradation due to saltwater intrusion in Kiribati and Tuvalu (Wairiu, 2017) and shoreline change in French Polynesia (Yates et al., 2013), Tuvalu (Kench et al., 2015, 2018) and Hawaii (Romine et al., 2013). Observations, models and other evidence indicate that unconstrained Pacific atolls have kept pace with SLR with little reduction in size or experienced a net gain in land (Kench et al., 2015, 2018; McLean and Kench, 2015; Beetham et al., 2017). Whilst islands are highly vulnerable to SLR (*high confidence, robust evidence*), they are also reactive to change. Small islands are impacted by multiple climatic stressers, with SLR being more important a stressor to some islands rather than others (Box 3.5, Section 3.4.10, Section 4.3.5.6, Box 4.3, 5.2.1, 5.5.3.3, Box 5.3).

Observations of adaptation to multiple drivers of coastal change, including SLR, include retreat (migration), accommodate and defend. Migration (internal and international) has always been important on small islands (Farbotko and Lazrus, 2012; Weir et al., 2017), with changing environmental and weather conditions (as a planned adaptation strategy) just one factor in the choice to migrate (Campbell and Warrick, 2014) (Sections 3.4.10, 4.3.5.6 and 5.3.2). Whilst flooding may result in migration or relocation for example, Vunidogoloa, Fiji, (McNamara and Des Combes, 2015; Gharbaoui and Blocher, 2016) or Soloman Islands (Albert et al., 2017), in-situ adaptation may be have been tried or preferred, for example stilted housing or raised floors in Tubigon, Bohol, Philippines (Jamero et al., 2017), raised roads and floors in Batasan and Ubay, Phillipines (Jamero et al., 2018) raised platforms for faluw in Leang, Federated States of Micronesia (Nunn et al., 2017). Protective features, such as seawalls or beach nourishment are observed to locally reduce erosion and flood risk, but can have other adverse implcations (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014; Section 29.6.22).

There is a lack of precise, quantitative studies of projected impacts of SLR at 1.5ºC and 2ºC. Small islands are projected to be at risk and very sensitive to coastal climate change and other stressors (high agreement, robust evidence) (Nurse et al., 2014; Benjamin and Thomas, 2016; Ourbak and Magnan, 2017; Brown et al., 2018a; Nicholls et al., 2018; Rasmussen et al., 2018; Section 29.3 and 29.4), such as oceanic warming, SLR (resulting in salinization, flooding and erosion), cyclones and mass coral bleaching and mortality (Section 3.4.4, Box 3.4, Box 3.5). These can have significant socio-economic and ecological implications, such as on health, agriculture and water resources, which have impacts for livlihoods (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014). Combinations of drivers causing adverse impacts are important: Storlazzi et al. (2018) found that the impacts of SLR and wave-induced flooding (within a temperature horizon equivalent of 1.5°C) could affect freshwater availability on Roi-Namur, Marshall Islands, but is also dependent on other extreme weather events, such as temperature. Freshwater may also be affected by a 0.40 m rise in sea-level (which may be experienced with a 1.5°C warming) in other Pacific atolls (Terry and Chui, 2012). Whilst SLR is a major hazard for atolls, islands of higher elevation are also threatened given there is often a lot of infrastructure located near to the coast (Kumar and Taylor, 2015; Nicholls et al., 2018). Tens of thousands of people on small islands are exposed to SLR (Rasmussen et al., 2018). Giardino et al. (2018) found that hard defence structures on the island of Ebeye in the Marshall Islands, were effective for longer time periods at the sea level rise associated with 1.5ºC and 2ºC. In Jamacia and St Lucia, SLR and extreme sea levels threaten transport system infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018). slower rates of SLR will provide greater opportunity for adaptation to be successful (*medium agreement*), but will not reduce it substantially enough on islands of the lowest elevation. Migration and/or relocation may be an adaptation option (Section 3.4.10). Thomas and Benjamin (2017) highlight three areas of concern in the context of loss and damage at 1.5°C: a lack of data, gaps in financial assessments, and a lack of targeted policies or mechanisms to address this (Cross-Chapter Box 12 in Chapter 5). Small islands remain vulnerable to SLR (*high confidence*).

3.4.5.4 Deltas and estuaries

Observations of SLR and human influence are felt through salinization leading to mixing in deltas and estuaries, aquifers, flooding (also enhanced by precipitation and river discharge), erosion land degradation, threatening freshwater sources and posing risks to ecosystems and human systems (Wong et al., 2014; Section 5.4). For instance, in the Delaware River Estuary on the USA east coast, upward trends of streamflow adjusted salinity (measured since the 1900s) accounting for the effects of streamflow and seasonal variations have been detected with SLR a potential cause (Ross et al., 2015).

Z. Yang et al. (2015) found that USA future climate scenarios (A1B 1.6°C and B1 2°C in the 2040s) had a greater effect on salinity intrusion than future land use/land cover change in the Snohomish River estuary, Washington state (USA). This resulted in a shift in the salinity both upstream and downstream in low flow conditions. Projecting impacts in deltas needs an understanding of both fluvial discharge and SLR, making projections complex as the drivers operate on different time and spatial scales (Zaman et al., 2017; Brown et al., 2018b) The mean annual flood depth when 1.5°C is first projected to be reached in the Ganges-Brahmaputra delta may be less than the most extreme annual flood depth seen today, taking account of SLR, plus surges, tides, bathymetry and local river flows (Brown et al., 2018b). Furthermore increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C of warming (Zaman et al., 2017). Salinisation could impact agriculture and food security (Cross-Chapter Box 6). For 1.5°C or 2°C stabilization conditions in 2200, or 2300 plus surges, a minimum of 44% of the the Bangladesh Ganges-Brahmaputra, Indian Bengal, Indian Mahanadi and Ghanese Volta deltas land area (without defences) would be exposed unless sedimentation occurs (Brown et al., 2018b). Other deltas are similarly vulnerable. SLR is one factor affecting deltas, and assessment of numerous geophysical and anthropogenic drivers of geomorphic change is important (Tessler et al., 2018). For example, dike building to reduce flooding and dam building (Gupta et al., 2012) restricts sediment movement and deposition leading to enhanced subsidence, which can occur at a greater rate than SLR (Auerbach et al., 2015; Takagi et al., 2016). Although dikes remain essential to reduce flood risk today, promoting sedimentation is an advisable strategy (Brown et al., 2018b) which may involve nature-based solutions. Transformative decisions regarding the extent of sediment restrictive infrastructure may need to be considered over centennial scales (Brown et al., 2018b). Thus in a 1.5°C or 2°C world, deltas, which are home to millions of people, are highly threatened from SLR and localised subsidence today, and over long time scales (*high confidence, medium evidence*).

3.4.5.5 Wetlands

Observations indicate that wetlands, such as saltmarshes and mangrove forests are disrupted by changing conditions (Wong et al., 2014; Lovelock et al., 2015; Section 5.4.2.4; Section 3.4.4.8), such as total water levels and sediment availability. For example, observations indicated that saltmarshes in Connecticut and New York measured from 1900 to 2012, have accreted with SLR, but have lost marsh surface relative to tidal datums, leading to increased marsh flooding and further accretion (Hill and Anisfeld, 2015). This stimulated marsh carbon storage, and aided climate change mitigation.

Salinisation may lead to shifts in wetland communities and their ecosystems functions, affecting freshwater wetlands (Herbert et al., 2015). Some projections of wetland change, with magnitudes (but not necessarily rates or timing) of SLR analogous at 1.5°C and 2°C, indicate a net loss (e.g., Cui et al., 2015 with a 2.6 mm yr-1 rise (aligning with AR5) in the Yangtze Estuary; Blankespoor et al., 2014) 1 m rise in multiple countries; Arnell et al. (2016) using an A1 SRES scenario of up to 0.48 m by 2050 on a global scale; drowning of 60% of marshes studied world-wide (with a rate of sea-level rise of 4.4 mm yr^{-1}) by 2100 (Crosby et al., 2016), whilst others report a net gain with wetland transgression ((Raabe and Stumpf, 2016) in the Gulf of Mexico). However, the feedback between wetlands and sea level is complex, with parameters such as lack of accommodation space restricting inland migration, or sediment supply and feedback between plant growth and geomorphology (Kirwan and Megonigal, 2013; Ellison, 2014; Martínez et al., 2014; Spencer et al., 2016) still being explored. Reducing global warming from 2oC to 1.5oC will deliver long-term benefits from lower SLR, allowing natural sedimentation rates to more likely keep up with SLR. It remains unclear how wetlands will respond and under what conditions (including other climate parameters) with a rise in 1.5°C and 2°C, simultaneously recognising they have great potential for adaptation and climate change mitigation (medium confidence, medium evidence) (Sections 4.3.2 and 4.3.3.3).

3.4.5.6 *Other coastal settings*

Numerous impacts have not been quantified at 1.5°C or 2°C but remain important. This includes systems identified in WGII AR5 (Wong et al., 2014; Section 5.4), such as beaches, barriers, sand dunes, rocky coasts, aquifers, lagoons and ecosystems (for the latter, see Section 3.4.4.12). For example, SLR effects erosion and accretion, and therefore sediment movement, instigating shoreline change (Wong et al., 2014; Section 5.4.2.1) which could affect land-based ecosystems. Global observations indicate no overall clear effect of SLR on shoreline change (Le Cozannet et al. (2014) as it is highly site specific (e.g., Romine et al. 2013) Infrastructure or geological constraints reduces shoreline movement causing coastal squeeze (e.g. in Japan, beach losses due to SLR are projected with a RCP2.6 scenario, and are projected to increase under RCP8.5 (Udo and Takeda, 2017)). Compound flooding (the combined risk of flooding from multiple drivers) has increased significantly over the past century in major coastal cities (Wahl et al., 2015) and is likely to increase with further development and SLR at 1.5°C and 2°C unless adaptation is undertaken. Thus SLR rise will have a wide range of adverse effects on coastal zones (*medium confidence*).

3.4.5.7 *Adapting to coastal change*

Adaptation to coastal change from SLR and other drivers is occurring today (high agreement, robust evidence, see Cross-Chapter Box 9 in Chapter 4) including migration, ecosystem-based adaptation, raising infrastructure and defences, salt-tolerant food production, early warning systems, insurance and education (Wong et al., 2014; Section 5.4.2.1). Climate change mitigation will reduce the rate of SLR this century, decreasing the need for extensive, and in places, immediate adaptation. Adaptation will reduce impacts in human settings (Hinkel et al., 2014; Wong et al., 2014) (*high agreement, robust evidence*), although there is less certainty for ecosystems (Sections 4.3.2, 4.3.3.3). While some ecosystems (e.g., mangroves) may be able to move shoreward as sea levels increase, coastal development (e.g., coastal building, seawalls, and agriculture) often interrupt these transitions (Saunders et al., 2014). Options for responding to these challenges include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development, and unsustainable aquaculture/agriculture. In some cases, restoration of coastal habitats and ecosystems can be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, intensifying storms, coastal inundation and salinization communities (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Spalding et al., 2014; Elliff and Silva, 2017).

Since the AR5, planned and autonomous adaptation and forward planning has become more wide-spread (Araos et al., 2016; Nicholls et al., 2018), but continued efforts are required as many localities are in the early stages of adapting or not adapting at all (Araos et al., 2016) (See Cross-Chapter Box 9 in Chapter 4). This is regional and sub-sectoral specific, and also linked to non-climatic factors (Ford et al., 2015; Lesnikowski et al., 2015; Araos et al., 2016). Adaptation pathways (e.g., Ranger et al., 2013; Barnett et al., 2014; Rosenzweig and Solecki, 2014; Buurman and Babovic, 2016) assist long-term thinking, but are not widespread practice despite knowledge of long-term risk (Section 4.2.2). Furthermore, retreat and human migration have increasingly being considered as a management response (Hauer et al., 2016; Geisler and Currens, 2017), with a growing emphasis on green adaptation. There are few studies on the adaptation limits to SLR where transformation change may be required (Wong et al., 2014, Section 5.5.8; Nicholls et al. 2015; Section 4.2.2.3). SLR poses a long-term threat (Section 3.3.9), even with 1.5°C and 2°C of warming centennial scale adaptation remains essential (high confidence, robust evidence).

Table 3.3: Land and people exposed to sea level rise (SLR, assuming no protection at all). Extracted from (Brown et al., 2018a; Goodwin et al., 2018). SSP: Shared Socioeconomic Pathway, wrt: with respect to

Climate scenario	**Impact factor, assuming there is no adaptation or protection at all (50th, [5th-95th percentiles])**	**Year**			
		2050	**2100**	**2200**	**2300**
1.5ºC	Temperature rise wrt 1850–1900 (°C)	1.71 (1.44-2.16)	1.60 (1.26-2.33)	1.41 (1.15-2.10)	1.32 (1.12-1.81)
	SLR (m) wrt 1986-2005	0.20 (0.14-0.29)	0.40 (0.26-0.62)	0.73 (0.47-1.25)	1.00 (0.59-1.55)
	Land exposed (x10^3 km^2)	574 [558-597]	620 [575-669]	666 [595-772]	702 [666-853]
	People exposed, SSP1-5 (millions)	127.9-139.0 [123.4-134.0, 134.5-146.4]	102.7-153.5 [94.8-140.7, 102.7-153.5]	--	133.8-207.1 [112.3-169.6, 165.2 - 263.4]*
2ºC	Temperature rise wrt 1850–1900 (° C)	1.76 (1.51-2.16)	2.03 (1.72-2.64)	1.90 (1.66-2.57)	1.80 (1.60-2.20)
	SLR (m) wrt 1986-2005	0.20 (0.14-0.29)	0.46 (0.30-0.69)	0.90 (0.58-1.50)	1.26 (0.74-1.90]
	Land exposed (10^3 km^2)	575 [558-598]	637 [585-686]	705 [618-827]	767 [642-937]
	People exposed, SSP1-5 (millions)	128.1-139.2 [123.6-134.2, 134.7-146.6]	105.5-158.1 [97.0-144.1, 118.1-179.0]	--	148.3 - 233.0 [120.3-183.4, 186.4-301.8]*

*Population is held static after 2300.

[START BOX 3.5 HERE]

Box 3.5: Small Island Developing States (SIDS)

1.5˚C warming is expected to prove a challenging state for Small Island Developing States (SIDS) that are already experiencing impacts associated with climate change. At 1.5˚C, compounding impacts from interactions between climate drivers may contribute to loss of, or change in, critical natural and human systems (*high agreement, medium evidence*). There are a number of reduced risks at 1.5˚C versus 2˚C, particularly when coupled with adaptation efforts (*high agreement, medium evidence*).

Changing climate hazards for SIDS at 1.5°C

Mean surface temperature is projected to increase in SIDS at 1.5˚C (*high agreement, robust evidence*). The Caribbean region will experience 0.5°C –1.5˚C warming compared to 1971–2000 baseline, with greatest warming over larger land masses (Taylor et al., 2018). Under the Representative Concentration Pathway (RCP)2.6 scenario, the western tropical Pacific is projected to experience warming of 0.5°C –1.7°C relative to 1961–1990. Extreme temperatures will also increase, with potential for elevated impacts as a result of comparably small natural variability (Reyer et al., 2017a). Compared to the 1971–2000 baseline, up to 50% of the year are projected to be under warm spell conditions in the Caribbean at 1.5˚C with a further increase by up to 70 days at 2˚C (Taylor et al., 2018).

Changes in precipitation patterns, freshwater availability and drought sensitivity differ between small island regions (*high agreement, medium evidence*). Some western Pacific and the northern Indian Ocean islands may see increased freshwater availability, while islands in most other regions are projected to see a substantial decline (Holding et al., 2016; Karnauskas et al., 2016). For several SIDS, approximately 25% of the overall freshwater stress projected under 2°C at 2030 can be avoided by limiting global warming to 1.5°C (Karnauskas et al., 2018). In accordance with an overall drying trend, an increasing drought risk is projected for Caribbean SIDS (Lehner et al., 2017) and moderate to extreme drought conditions are projected to be about 9% longer on average for 2°C versus 1.5°C for islands in this region (Taylor et al., 2018).

Projected changes in the ocean system at higher warming targets (Section 3.4.4), including potential changes in circulation (Section 3.3.7) and increases in both surface temperatures (Section 3.3.7) and ocean acidification (Section 3.3.10) suggest steadily increasing risks for SIDS associated with warming levels close to and exceeding 1.5°C.

Differences in global sea level between 1.5°C and 2°C depend on the time scale considered and will fully materialize only after 2100 (Section 3.3.9). Projected changes in regional sea level are similarly time dependent, but generally found to be above global average for tropical regions including small islands (Kopp et al., 2014; Jevrejeva et al., 2016). Sea level related threats for SIDS, for example, from salinisation, flooding, permanent inundation, erosion and pressure on ecosystems, will therefore persist well beyond the 21st century even under 1.5°C warming (Section 3.4.5.3; Nicholls et al., 2018). Prolonged interannual sea level inundations may increase throughout the tropical Pacific with ongoing warming and in the advent of increased frequency of extreme La Niña events, exacerbate coastal impacts of projected global mean Sea Level Rise (SLR; Widlansky et al., 2015). Changes to frequency of extreme El Niño and La Niña events may also increase the frequency of droughts and floods in South Pacific islands (Cai et al., 2012; Box 4.2; Section 3.5.2)

Extreme precipitation in small island regions is often linked to tropical storms and contributes to the climate hazard (Khouakhi et al., 2017). Similarly, extreme sea levels for small islands, particularly in the Caribbean, are linked to tropical cyclone occurrence (Khouakhi and Villarini, 2017). Under a 1.5°C stabilization scenario, there is a projected decrease in the frequency of weaker tropical storms and an increase in the number of intense cyclones (Section 3.3.6, Wehner et al., 2017). There are insufficient studies to assess differences in tropical cyclone statistics for 1.5°C versus 2°C (Section 3.3.6). There are considerable differences in the adaptation responses to tropical cyclones across SIDS (Cross-Chapter Box 11 in Chapter 4).

Impacts on key natural and human systems

Projected increases in aridity and decreases in freshwater availability at 1.5°C, along with additional risks from SLR and increased wave-induced run-up, might leave several atoll islands uninhabitable (Storlazzi et al., 2015; Gosling and Arnell, 2016). Changes in availability and quality of freshwater linked to a combination of changes to climate drivers may adversely impact SIDS' economies (White and Falkland, 2010; Terry and Chui, 2012; Holding and Allen, 2015; Donk et al., 2018). Growth-rate projections based on temperature impacts alone indicate robust negative impacts on GDP per capita growth for SIDS (Petris et al., 2018, Section 3.4.7.1, Section 3.4.9.1, Section 3.5.4.9). These impacts are reduced considerably under 1.5°C but may be increased by escalating risks from climate related extreme weather events and SLR (Section 3.4.5.3, Section 3.4.9.4, Section 3.5.3)

Marine systems and associated livelihoods in SIDS face higher risks at 2°C as compared to 1.5°C (*high agreement, medium evidence*). Mass coral bleaching and mortality are projected to increase due to interactions between rising ocean temperatures, ocean acidification, and destructive waves from intensifying storms (Section 3.4.4, Box 3.4, Section 5.2.3). At 1.5°C, approximately 70–90% of global coral reefs are projected to be at risk of long-term degradation due to coral bleaching, increasing to 99% at 2°C (Schleussner et al., 2016b). Warmer temperatures are also related to an increase in coral disease development, leading to coral degradation (Maynard et al., 2015). For marine fisheries, limiting warming to 1.5°C decreases the risk of species extinction and declines in maximum catch potential, particularly for small islands in tropical oceans (Cheung et al., 2016a).

Long term risks of coastal flooding and impacts on population, infrastructure and assets are projected to increase with higher levels of warming (*high agreement, robust evidence*). Tropical regions including small islands are expected to experience the largest increases in coastal flooding frequency with the frequency of extreme water-level events in small islands projected to double by 2050 (Vitousek et al., 2017). Wave driven coastal flooding risks for reef-lined islands may increase as a result of coral reef degradation and SLR (Quataert et al., 2015). Exposure to coastal hazards is particularly high for SIDS, with a significant share of population, infrastructure and assets at risk (Scott et al., 2012; Kumar and Taylor, 2015; Rhiney, 2015; Byers et al., 2018; Section 3.4.9, Section 3.4.5.3). Limiting warming to 1.5°C instead of 2°C spares the inundation of lands currently home to 60,000 individuals in SIDS by 2150 (Rasmussen et al., 2018). However, such estimates do not take into account shoreline response (Section 3.4.5) or adaptation.

Risks of impacts across sectors are higher at 1.5°C as compared to the present, and will further increase at 2°C (*high agreement, medium evidence*). Projections indicate that at 1.5°C there will be increased incidents of internal migration and displacement (Albert et al., 2017, Sections 3.5.5, 4.3.6, 5.2.2), limited capacity to assess loss and damage (Thomas and Benjamin, 2017) and substantial increases in risk to critical transportation infrastructure from marine inundation (Monioudi et al., 2018). The difference between 1.5°C and 2°C might exceed limits for normal thermoregulation of livestock animals and result in persistent heat stress for livestock animals in SIDS (Lallo et al., 2018).

At 1.5C limits to adaptation will be reached for several key impacts in SIDS resulting in residual impacts and loss and damage (Cross-Chapter Box 12 in Chapter 5, Section 1.1.1). There are a number of reduced risks when limiting temperature increase to 1.5°C versus 2°C, particularly when coupled with adaptation efforts that take into account sustainable development (Mycoo, 2017; Thomas and Benjamin, 2017; Section 3.4.2, Box 4.3, Section 5.6.3.1, Box 5.3). Region-specific pathways for SIDS exist to address climate change (Section 5.6.3.1, Box 5.3, Box 4.6, Cross-Chapter Box 11 in Chapter 4).

[END BOX 3.5 HERE]

3.4.6 *Food, nutrition security and food production systems (including fisheries and aquaculture)*

3.4.6.1 *Crop production*

Quantifying the observed impacts of climate change for food security and food production systems requires assumptions about the many non-climate variables that interact with climate change variables. Implementing specific strategies can partly or greatly alleviate the climate change impacts on these systems (Wei et al., 2017), whilst the degree of compensation is mainly dependent on geographical area and crop type (Rose et al., 2016). Despite these issues, recent studies confirm that observed climate changes have already affected crop suitability in many areas, resulting in changes in the production levels of the main agricultural crops. These impacts are evident in many areas of the world ranging from Asia (C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016) to America (Cho and McCarl, 2017) and Europe (Ramirez-Cabral et al., 2016), particularly affecting typical local crops cultivated in specific climate conditions (e.g., Mediterranean crops like olive and grapevine, (Moriondo et al., 2013a, b).

Temperature and precipitation trends have reduced crop production and yields, with the most negative impacts on wheat and maize (Lobell et al., 2011), whilst the effects on rice and soybean yields are less clear and may be positive or negative (Kim et al., 2013; van Oort and Zwart, 2018). Warming has resulted in positive effects on crop yield in some high-latitude areas (Jaggard et al., 2007; Supit et al., 2010; Gregory and Marshall, 2012; C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016; Daliakopoulos et al., 2017), also suggesting the possibility of more than one harvest per year (B. Chen et al., 2014; Sun et al., 2015). Climate variability was found to explain more than 60% of the of maize, rice, wheat and soybean yield variations in the main global breadbaskets areas (Ray et al., 2015), with variation in the percentage according to crop type and scale (Moore and Lobell, 2015; Kent et al., 2017). Climate trends explain also change in the lengthening of the growing season, where greater modifications were found in the northern latitude areas (Qian et al., 2010; Mueller et al., 2015).

The rise in tropospheric ozone has already reduced yields of wheat, rice, maize, and soybean ranging from 3% to 16% globally (Van Dingenen et al., 2009). Some studies found that increases in atmospheric CO_2 concentrations would be expected to increase yields by enhancing radiation and water use efficiencies (Elliott et al., 2014; Durand et al., 2017). In open-top chamber experiments at elevated CO_2 and 1.5°C warming, maize and potato yields were observed to increase by 45.7% and 11%, respectively (Singh et al. 2013; Abebe et al., 2016). However, observations of actual crop yield trends indicate that reductions as a result of climate change remain more common than crop yield increases, despite increased atmospheric CO_2 concentration (Porter et al., 2014). For instance, McGrath and Lobell (2013) indicated that production stimulation at increased atmospheric CO_2 concentration was mostly driven by differences in climate and crop species, whilst yield variability due to elevated CO_2 was only about 50–70% of the variability due to climate. However, importantly, the faster growth rates induced by elevated CO_2 often coincided with lower protein values in several important C3 cereal grains (Myers et al., 2014) although perhaps not always for C4 grains such as sorghum under drought conditions (De Souza et al., 2015). Elevated CO_2 concentrations of 568–590 ppm alone (a range that corresponds approximately to RCP6 in the 2080s and hence a warming of 2.3–3.3°C (van Vuuren et al., 2011a, WGI Table 12.2) alone reduced the protein, micronutrient, and B vitamin content of the 18 rice cultivars grown most widely grown in southeast Asia, where it is a staple food source, by an amount sufficient to create nutritional-related health risks for 600 million people (Zhu *et al.* 2018). Overall, the effects of increased CO_2 concentration alone during the 21st century are therefore expected to have a negative impact on global food security (*medium confidence*).

Crop yields in the future will also be affected by projected changes in temperature and precipitation. Studies of major cereals showed that maize and wheat yields begin to decline with 1°C –2°C of local warming and under nitrogen stress conditions at low latitudes (Porter et al., 2014; Rosenzweig et al., 2014) (*high confidence*). A few studies since the AR5 have focused on the impacts on cropping systems for scenarios where global mean temperatures increase within 1.5°C. (Schleussner et al., 2016b) projected that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and Central and South America. Ricke et al. (2015) highlighted that cropland stability declines rapidly between 1ºC and 3ºC warming, whilst Bassu et al. (2014) suggested that an increase of air temperature negatively influence the modeled maize yield response of –0.5 t ha^{-1} per degree Celsius, as also reported by Challinor et al. (2014) for tropical regions. Niang et al. (2014) projected significantly lower risks to crop productivity in Africa at 1.5ºC compared to 2ºC warming. Lana et al. (2017) indicated that the impact of temperature increases on crop failure of maize hybrids was much greater as temperatures increase to +2°C compared to 1.5°C (*high confidence*). J. Huang et al. (2017) found that limiting warming at +1.5 °C compared to +2°C, maize yield losses would be reduced over drylands. Although Rosenzweig et al. (2017, 2018) did not find a clear distinction between yield declines or increases in some breadbasket regions between the two temperature levels, these studies generally did find declines in breadbasket regions when the effects of CO_2 fertilization were excluded. Iizumi et al. (2017) found lower maize and soybean yields reduction at +1.5°C than at +2°C, higher rice production at +2°C than at +1.5°C warming and no clear differences for wheat at global mean basis. These results were largely consistent with other studies (Faye et al., 2018; Ruane et al., 2018). In the western Sahel and southern Africa, moving from 1.5°C to 2°C warming was projected to result in further reduction of maize, sorghum and cocoa cropping areas suitability as well as yield losses especially for C3, only partially compensated by rainfall change (Läderach et al., 2013; World Bank, 2013; Sultan and Gaetani, 2016).

Some studies found a significant reduction in global production of wheat rice, maize, and soybean of 6.0 ± 2.9%, 3.2 ± 3.7%, 7.4 ± 4.5% and 3.1%, respectively, for each degree Celcius increase in global mean temperature (Asseng et al. 2015; C. Zhao et al., 2017). Similarly, Li et al. (2017) indicated a significant reduction in rice yields by about 10.3% in the greater Mekong sub-region (*medium confidence*). Large rice and maize yield losses are to be expected in China due to climate extremes (Wei et al., 2017; Zhang et al., 2017) (*medium confidence*).

Crop production is also negatively affected also by a factor generally excluded from the aforementioned studies, that is the increase in both direct and indirect climate extremes. Direct extremes include changes in rainfall extremes (Rosenzweig et al., 2014), increases in hot nights (Welch et al., 2010; Okada et al., 2011)); extremely high daytime temperature (Schlenker and Roberts, 2009; Jiao et al., 2016, Lesk et al., 2016); drought (Jiao et al., 2016; Lesk et al., 2016), heat stress (Deryng et al., 2014, Betts et al., 2018), flood (Betts et al., 2018; Byers et al., 2018), chilling damage, (Jiao et al., 2016), while indirect effects include the spread of pest and diseases (van Bruggen et al., 2015, Jiao et al., 2014), which can also have detrimental effects on cropping systems.

Taken together, the findings of studies on the effects of changes in temperature, precipitation, changes in CO_2 concentration and extreme weather events indicate that a global warming of 2°C is projected to result in a greater reduction in global crop yields and global nutrition than a global warming of 1.5°C (*high confidence,* Section 3.6).

3.4.6.2 *Livestock production*

Studies of climate change impacts on livestock production are few in number. Climate change is expected to directly affect yield quantity and quality (Notenbaert et al., 2017), beside indirectly impacting the livestock sector through feed quality changes and spread of pests and diseases (Kipling et al., 2016) (*high confidence*). Increased warming and its extremes are expected to cause changes in physiological processes in livestock (i.e., thermal distress, sweating and high respiratory rates) (Mortola and Frappell, 2000) and to have detrimental effects on animal feeding, growth rates (André et al., 2011; Renaudeau et al., 2011; Collier and Gebremedhin, 2015) and reproduction (De Rensis et al., 2015). Wall et al. (2010) observed reduced milk yields and increased cow mortality as the impact of heat stress on dairy cow production over some UK regions, whilst reduction in water supply might increase cattle water demand (Masike and Urich, 2008). Generally, heat stress can be responsible for domestic animal mortality increase and economic losses (Vitali et al., 2009), affecting a wide range of reproductive parameters (e.g., embryonic development and reproductive efficiency in pigs, Barati et al., 2008; ovarian follicle development and ovulation in horses, Mortensen et al., 2009).

Much attention has also been dedicated to ruminant diseases (e.g., liver fluke, Fox et al., 2011; blue-tongue virus, Guis et al., 2012; Foot-and-Mouth Disease (FMD), Brito et al. (2017); or zoonotic diseases, Njeru et al., 2016; Simulundu et al., 2017).

Future climate change impacts on livestock are expected to increase. In temperate climates, warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Similar studies confirmed decrease in forage quality both for natural grassland in France (Graux et al., 2013) and sown pastures in Australia (Perring et al., 2010). Water resources availability for livestock are expected to decrease due to increased runoff and reduced groundwater resource. Increased temperature will likely induce changes in river discharge and basins water amount, leading human and livestock populations to experience water stress especially over the driest areas (Palmer et al., 2008) (i.e., sub-Saharan Africa and South Asia) (*medium confidence*). Elevated temperatures are also expected to increase methane production (M.A. Lee et al., 2017; Knapp et al., 2014). Globally, a decline in livestock of more 7.5-9.6% is expected at about 2°C warming, with associated economic losses of between $9.7 and $12.6 billion (Boone et al., 2017).

3.4.6.3 Fisheries and aquaculture production

Global fisheries and aquaculture contribute a total of 88.6 and 59.8 million tons from capture and aquaculture (FAO, 2016), playing an important role in food security of a large number of countries (McClanahan et al., 2015; Pauly and Charles, 2015) and resulting essential to meet the protein demand of a growing global population (Cinner et al., 2012, 2016; FAO, 2016; Pendleton et al., 2016). A steady increase in the risks associated with bivalve fisheries and aquaculture at mid-latitude is coincident with increases in temperature, ocean acidification, introduced species, disease and other drivers (Lacoue-Labarthe et al., 2016; Clements et al., 2017; Clements and Chopin, 2017; Parker et al., 2017). Sea level rise and storm intensification pose a risk to hatcheries and other infrastructure (Callaway et al., 2012; Weatherdon et al., 2016), whilst others risks are associated with the invasion of parasites and pathogens (Asplund et al., 2014; Castillo et al., 2017). Human actions have reduced the risks from these factors which are expected to be more likely moderated under RCP2.6 and very high under RCP8.5 (Gattuso et al., 2015). The climate related risks for fin fish (Section 3.4.4) are producing a number of challenges for small scale fisheries (e.g., (Kittinger, 2013; Pauly and Charles, 2015; Bell et al., 2017). Recent literature (2015–2017) described growing threats from the rapid shifts in the biogeography of key species (Poloczanska et al., 2013, 2016; Burrows et al., 2014; García Molinos et al., 2015) and the ongoing rapid degradation of key ecosystems such as coral reefs, seagrass and mangroves (Section 3.4.4; Box 3.4). The acceleration of these changes, coupled with non-climate stresses (e.g., pollution, overfishing, unsustainable coastal development), drive many small-scale fisheries well below the sustainable harvesting levels required to maintain these resources as a source of food (McClanahan et al., 2009, 2015; Cheung et al., 2010; Pendleton et al., 2016). As a result, projections of climate change and the growth in human population increasingly project scenarios that include shortages of fish protein for many regions (e.g., Pacific Ocean, Bell et al., 2013; 2017); Indian Ocean, for example, (McClanahan et al., 2015). Mitigation of these risks involves marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Kittinger, 2013; McClanahan et al., 2015; Song and Chuenpagdee, 2015; Weatherdon et al., 2016). Other threats concern the increasing incidence of alien species and diseases (Kittinger et al., 2013; Weatherdon et al., 2016).

Risks of climate change related impacts on low latitude fin fisheries are low today, but are expected to reach very high levels under all RCPs especially at low latitudes (*high confidence*) by 1.1ºC. Projections for mid to high latitude fisheries include increases in fishery productivity in some cases (Cheung et al., 2013; Hollowed et al., 2013; Lam et al., 2014; FAO, 2016). These are associated with the biogeographical shift of species towards higher latitudes (Fossheim et al., 2015) which brings benefits as well as challenges (e.g., increased risk of disease and invasive species). Factors underpinning the expansion of fisheries production to high latitude locations include warming, increased light levels and mixing due to retreating sea ice (Cheung et al., 2009), resulting in substantial increases in primary productivity and fish harvesting in the North Pacific and North Atlantic (Hollowed and Sundby, 2014).

Present day risks for mid latitude bivalve fisheries and aquaculture are low up to 1.3ºC, *moderate* at 1.3ºC, and *moderate* to *high* up to 1.9ºC (Figure 3.17). For instance, Cheung et al. (2016a), simulating the loss in fishery productivity at 1.5°C, 2ºC and 3.5°C above the preindustrial period, found that the potential global catch for marine fisheries will *likely* decrease by more than 3 million metric tons for each degree of warming. Low latitude finfish fisheries have higher risks of impacts, with present day risks being moderate and becoming high risks at 1.5˚C and 2˚C. High latitude fisheries are undergoing major transformations, and while production is increasing, present day risk is moderate, and remains at moderate at 1.5˚C and 2˚C (Figure 3.3).

Adaptation measures can be applied to shellfish, large pelagic fish resources and biodiversity and include options such as protecting reproductive stages and brood stock from periods of high Ocean Acidification (OA), stock selection for high tolerance to OA (Ekstrom et al., 2015; Rodrigues et al., 2015; Handisyde et al., 2016; Lee, 2016; Weatherdon et al., 2016; Clements and Chopin, 2017) (*high confidence*), redistribution of highly migratory resources (Pacific tuna) (*high confidence*), governance instruments such as international fisheries agreements (Lehodey et al., 2015; Matear et al., 2015), protection and regeneration of reef habitats, reduction of coral reefs stresses and development of alternative livelihoods (e.g., aquaculture, Bell et al., 2013, 2017).

Cross-Chapter Box 6: Food Security

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Climate change influences food and nutritional security through its effects on food availability and quality, access, and distribution (Paterson and Lima, 2010; Thornton et al., 2014; FAO, 2016). More than 815 million people were undernourished in 2016; 11% of the world's population, with higher proportions of populations in Africa (20%), southern Asia (14.4%) and the Caribbean (17.7%), with recent decreases in food security (FAO et al., 2017). Overall, food security is expected to be reduced at 2°C warming compared to 1.5°C warming, due to projected impacts of climate change and extreme weather on crop nutrient content and yields, livestock, fisheries and aquaculture (Sections 3.4.4.12 and 3.4.3.6), and land use (cover type and management) (*high confidence;* Section 3.4.6). The impacts of climate change on yield, area, pests, price, and food supplies are projected to have major implications for sustainable development, poverty eradication, inequality, and the ability for the international community to meet the United Nations Sustainable Development Goals (SDGs; Cross-Chapter Box 4 in Chapter 1)

Goal 2 of the SDGs aims to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture by 2030. This builds on the Millennium Development Goal (MDG); efforts to achieve Goal 1 reduced the proportion of undernourished people in low- and middle-income countries from 23.3% in 1990 to 12.9% in 2015. Climate change threatens the possibility of achieving SDG 2 and could reverse the progress made. Food security and agriculture are also critical to other aspects of sustainable development, including eradicating poverty (SDG 1), health and wellbeing (SDG 3), clean water (SDG 6), decent work (SDG 8) and the protection of ecosystems on land and water (SDG 14 and SDG 15) (UN, 2015, 2017; Pérez-Escamilla, 2017).

Increasing global temperatures pose large risks to food security globally and regionally, especially at low latitude areas (Cheung et al., 2010; Rosenzweig et al., 2013; Porter et al., 2014; Rosenzweig and Hillel, 2015; Lam et al., 2016) with warming of 2°C projected to result in a greater reduction in global crop yields and global nutrition than a global warming of 1.5°C (*high confidence,* Section 3.4.6) owing to the combined effects of changes in temperature, precipitation, and changes in extreme weather events and in CO_2 concentrations. Climate change can exacerbate malnutrition, reducing nutrient availability and quality of food products (Cramer et al., 2014; Springmann et al., 2016); *medium confidence*). Generally, vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C (Cheung et al., 2016a; Betts et al., 2018) , whilst at 2°C these are expected to be exacerbated especially in regions such as the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high confidence*).

Rosenzweig et al. (2018) and Ruane et al. (2018) report that the higher CO_2 concentrations at 2ºC caused positive effects in some regions compared to 1.5ºC. Production can also benefit from warming in higher latitudes with fertile soils, crop, and grassland, in contrast to the situation at low latitudes (Section 3.4.6) and similar benefits could arise for high latitude fisheries production (*high confidence*; Section 3.4.6.3). Studies exploring regional climate change risks on crop production are strongly influenced by the use of alternative regional climate change projections and the assumed strength of CO_2 fertilisation effects (Section 3.6) which are uncertain. For C3 crops, theoretically advantageous CO_2 fertilisation effects may not be realized in the field; further, they are often accompanied by losses in protein and nutrient content of crops (Section 3.6) and hence these projected benefits may not be realized. In addition, some micronutrients such as iron and zinc will be less accumulated and less available in food (Myers *et al.*, 2014). Together, the impacts on protein availability may take as many as 150 million people into protein deficiency by 2050 (Medek *et al.*, 2017). However, short-term benefits could arise for high latitude fisheries production as waters warm, sea ice contracts and primary productivity increases due to climate change (Cheung et al., 2010; Hollowed and Sundby, 2014; Lam et al., 2016; Sundby et al., 2016; Weatherdon et al., 2016) (*high confidence*; Section 3.4.6.3).

Factors affecting projections of food security include variability in regional climate projections, climate change mitigation (where this affects land use; see Section 3.6 and Crosss-Chapter Box 7) and biological responses (McGrath and Lobell, 2013; Elliott et al., 2014; Pörtner et al., 2014; Durand et al., 2017; AR5 6.5.1) (*medium confidence*; Section 3.4.6.1), extreme events (droughts, floods) (Rosenzweig et al., 2014; Wei et al., 2017) (*high confidence*; Sections 3.4.6.1, 3.4.6.2), financial volatility (Kannan et al., 2000; Ghosh, 2010; Naylor and Falcon, 2010; HLPE, 2011) and the distributions of pests and disease (van Bruggen et al., 2015; Jiao et al., 2014). Changes in temperature and precipitation are projected to increase global food prices by 3–84% by 2050 (IPCC, 2013). Differences in price impacts of climate change are accompanied by differences in land use change (Nelson et al., 2014b), energy policies and food trade (Mueller et al., 2011; Wright, 2011; Roberts and Schlenker, 2013). Fisheries and aquatic production systems (aquaculture) face similar challenges to those of crop and livestock sectors (Asiedu et al., 2017a, b; Utete et al., 2018; Section 3.4.6.3). Human influences on food security include demography, food wastage, diet shift, incomes and prices, storage, health status, trade patterns, conflict, and access to land and government or other assistance (Chapters 4 and 5). Across all these systems, the efficiency of adaptation strategies is uncertain, because it is strongly linked with future economic and trade environments and their response to changing food availability (Lobell et al., 2011; von Lampe et al., 2014; d'Amour et al., 2016; Wei et al., 2017) (*medium confidence*).

Climate change impacts on food security can be reduced through adaptation (Hasegawa et al., 2014). While climate change is very likely to decrease agricultural yield, the consequences could be reduced substantially at 1.5ºC with appropriate investment (Neumann et al., 2010; Muller, 2011; Roudier et al., 2011), awareness-raising to help inform farmers of new technologies for maintaining yield, and strong adaptation strategies and policies that develop sustainable agricultural choices (Sections 4.3.2 and 4.5.3). In this regard, initiatives such as 'climate smart' food production and distribution systems may assist adaptation via technologies and adaptation strategies for food systems (Lipper et al., 2014; Martinez-Baron et al., 2018; Whitfield et al., 2018) as well as meet mitigation goals (Harvey et al., 2014).

K.R. Smith et al. (2014) concluded that climate change will negatively affect childhood undernutrition and stunting through reduced food availability, and will negatively affect undernutrition-related childhood mortality and increase disability-adjusted life years lost, with the largest risks in Asia and Africa (Ishida et al., 2014; Hasegawa et al., 2016; Springmann et al., 2016; Annex 3.1 Table S11). Studies comparing the health risks associated with food insecurity at 1.5°C and 2°C concluded that risks are higher and the globally undernourished population larger at 2°C (Hales et al., 2014; Ishida et al., 2014; Hasegawa et al., 2016). Climate change impacts on dietary and weight-related risk factors were projected to increase mortality due to global reductions in food availability and consumption of fruit, vegetables, and red meat (Springmann et al., 2016). Further, temperature increases are reducing the protein and micronutrient content of major cereal crops, which is expected to further affect food security (Myers et al., 2017) (Zhu et al. 2018).

Strategies for improving food security often do so in complex settings such as the Mekong River Basin in South-East Asia. The Mekong is a major food bowl (Smajgl et al., 2015) yet is also a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014). It is also a useful illustration of the complexity of adaptation choices and actions in a 1.5˚C world. Climate projections indicate increased annual average temperatures and precipitation (Zhang et al., 2016) and increased flooding and related disaster risks (T.F. Smith et al., 2013; Ling et al., 2015; Zhang et al., 2016). Sea level rise and saline intrusion are ongoing risks to agricultural systems (Renaud et al., 2015). The main climate impacts in the Mekong will be on ecosystem health through salinity intrusion, biomass reduction, and biodiversity losses (Le Dang et al., 2014; Smajgl et al., 2015); agricultural productivity and food security (Smajgl et al., 2015); livelihoods such as fishing and farming (D. Wu et al., 2013); and disaster risk (D. Wu et al., 2013; Hoang et al., 2016) with implications for human mortality and economic and infrastructure losses.

Adaptation imperatives and costs in the Mekong will be higher under increased temperatures via impacts on agriculture and aquaculture, hazard exposure, and infrastructure. Adaptation measures to meet food security include greater investment in crop diversification and integrated agriculture-aquaculture practices (Renaud et al., 2015), improving water use technologies (e.g., irrigation, pond capacity improvement, rainwater harvesting), soil management, crop diversification, and strengthening allied sectors such as livestock rearing and aquaculture (ICEM, 2013). Ecosystem-based approaches, such as integrated water resources management, demonstrate successes in mainstreaming adaptation into existing strategies (Sebesvari et al., 2017). However, some of these adaptive strategies can have negative impacts that deepen the divide between land-rich and land-poor farmers (Chapman et al., 2016). Construction of high dikes for example has enabled triple-cropping with benefits for land-wealthy farmers but increasing debt for land-poor farmers (Chapman and Darby, 2016).

Institutional innovation has happened through the establishment of the Mekong River Commission (MRC) in 1995, an intergovernmental body between Cambodia, Lao PDR, Thailand and Viet Nam. The MRC has facilitated impact assessment studies, regional capacity building, and local project implementation (Schipper et al., 2010), although mainstreaming of adaptation into development policies has lagged behind needs (Gass et al., 2011). Existing adaptation interventions can be strengthened through improving flexibility of institutions dealing with land use planning and agricultural production, improved monitoring of saline intrusion, and setting up early warning systems that can be accessed by the local authorities or farmers (Renaud et al., 2015; Hoang et al., 2016; Tran et al., 2018). It is critical to identify and invest in synergistic strategies from an ensemble of infrastructural options (e.g., building dikes); soft adaptation measures (e.g., land-use change) (Smajgl et al., 2015; Hoang et al., 2018); combinations of top-down government-led (e.g., relocation) and bottom-up household strategies (e.g., increasing house height) (Ling et al., 2015); and community-based adaptation initiatives that merge scientific knowledge with local solutions (Gustafson et al., 2016, 2017; Tran et al., 2018). Critical attention needs to be given to strengthening social safety nets and livelihood assets whilst ensuring that adaptation plans are mainstreamed into broader development goals (Sok and Yu, 2015; Kim et al., 2017). The complexity of environmental, social and economic pressure on people in the Mekong River Basin highlights the complexity of climate impacts and adaptation in this region, and the fact that costs are likely to be much lower at 1.5°C than 2°C.

[END BOX X-B 3.1 HERE]

3.4.7 Human health

Climate change adversely affects human health by increasing exposure and vulnerability to climate-related stresses, and decreasing the capacity of health systems to manage changes in the magnitude and pattern of climate-sensitive health outcomes (Cramer et al., 2014; Hales et al., 2014). Changing weather patterns are associated with shifts in the geographic range, seasonality, and intensity of transmission of selected climate-sensitive infectious diseases (e.g., Semenza and Menne, 2009), and increasing morbidity and mortality are associated with extreme weather and climate events (e.g., K.R. Smith et al., 2014). Health detection and attribution studies conducted since the AR5 provided evidence using multi-step attribution that climate change is negatively affecting adverse health outcomes associated with heatwaves; Lyme disease in Canada; and *Vibrio* emergence in northern Europe (Mitchell, 2016; Mitchell et al., 2016; Ebi et al., 2017). The IPCC AR5 concluded there is *high* to *very high confidence* that climate change will lead to greater risks of injuries, disease and death due to more intense heatwaves and fires; increased risks of undernutrition; and consequences of reduced labor productivity in vulnerable populations (K.R. Smith et al., 2014).

3.4.7.1 Projected risk at 1.5°C and 2°C

Annex 3.1, Tables S7, S8 and S9 (based on Ebi et al., 2018) summarize the projected risks to human health of warming of 1.5°C and 2°C from studies of temperature-related morbidity and mortality, air quality and vector borne diseases assessed in and since the AR5. Other climate-sensitive health outcomes, such as diarrheal diseases, mental health and the full range of sources of poor air quality, were not considered because of the lack of projections of how risks could change at 1.5°C and 2°C. Few projections were for specific temperatures above pre-industrial temperature; Annex 3.1, Table S6 provides the conversions used to translate risks projected at particular time slices to temperature change (Ebi et al., 2018).

Temperature-related morbidity and mortality: The magnitude of projected heat-related morbidity and mortality is greater at 2°C than at 1.5°C (*very high confidence*) (Doyon et al., 2008; Jackson et al., 2010; Hanna et al., 2011; Huang et al., 2012; Petkova et al., 2013; Hajat et al., 2014; Hales et al., 2014; Honda et al., 2014; Vardoulakis et al., 2014; Garland et al., 2015; Huynen and Martens, 2015; Li et al., 2015; Schwartz et al., 2015; L. Wang et al., 2015; Guo et al., 2016; T.T. Li et al., 2016; Chung et al., 2017; Kendrovski et al., 2017; Arnell et al., 2018; Mitchell, 2018). The number of people exposed to heat events is projected to be greater at 2°C than at 1.5°C (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018). The extent to which morbidity and mortality increase varies by region, presumably because of acclimatization, population vulnerability, the built environment, access to air conditioning and other factors (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018). Populations at highest risk include older adults, children, women, those with chronic diseases, and people taking certain medications (*very high confidence*). Assuming adaptation takes place reduces the projected magnitude of risks (Hales et al., 2014; Huynen and Martens, 2015; Li et al., 2016b).

In some regions, cold-related mortality is projected to decrease with warmer temperatures, although increases in heat-related mortality generally are projected to outweigh any reductions in cold-related mortality with warmer winters, with the heat-related risks increasing with greater degrees of warming (Huang et al., 2012; Hajat et al., 2014; Vardoulakis et al., 2014; Gasparrini et al., 2015; Huynen and Martens, 2015; Schwartz et al., 2015).

Occupational health: Higher ambient temperatures and humidity levels place additional stress placed on individuals engaging in physical activity. Safe work activity and worker productivity during the hottest months of the year would be increasingly compromised with additional climate change (*medium agreement, low evidence*) (Dunne et al., 2013; Kjellstrom et al., 2013, 2017; Sheffield et al., 2013; Habibi Mohraz et al., 2016). Patterns of change may be complex; for example, at 1.5°C, there could be about a 20% reduction in areas experiencing severe heat stress in East Asia, compared to significant increases in low latitudes at 2°C (Lee and Min, 2018). The costs of preventing workplace heat-related illnesses through worker breaks suggest the difference in economic loss between 1.5°C and 2°C could be approximately 0.3% global GDP in 2100 (Takakura et al., 2017). In China, taking into account population growth and employment structure, high temperature subsidies for employees working on extremely hot days are projected to increase from 38.6 billion yuan yr^{-1} in 1979–2005 to 250 billion yuan yr^{-1} in the 2030s (about 1.5°C) (Zhao et al., 2016).

Air quality: Because ozone formation is temperature dependent, projections focusing only on temperature increase generally conclude that ozone-related mortality will increase with additional warming, with the risks higher at 2°C than at 1.5°C (*high confidence*) (Heal et al., 2013; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Dionisio et al., 2017; J.Y. Lee et al., 2017); Annex 3.1 Table S.8) reductions in precursor emissions would reduce future ozone concentrations (and associated mortality). Changes in projected PM-related mortality could increase or decrease, depending on climate projections and emissions assumptions (Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Table S8).

Malaria: Recent projections of the potential impacts of climate change on malaria globally and for Asia, Africa, and South America (Annex 3.1 Table S9) confirm that weather and climate are among the drivers of the geographic range, intensity of transmission, and seasonality of malaria, and that the relationships are not necessarily linear, resulting in complex patterns of changes in risk with additional warming (*very high confidence*) (Ren et al., 2016; Song et al., 2016; Semakula et al., 2017). Projections suggest the burden of malaria could increase with climate change because of a greater geographic range of the *Anopheles* vector, longer season, and/or increase in the number of people at risk, with larger burdens with greater amounts of warming, with regionally variable patterns (*high agreement, medium evidence*). Vector populations are projected to shift with climate change, with expansions and reductions depending on the degree of local warming, the ecology of the mosquito vector, and other factors (Ren et al., 2016).

***Aedes* (mosquito vector for dengue fever, chikungunya, yellow fever, and Zika virus):** Projections of the geographic distribution of *Aedes aegypti* and *Ae. albopictus* (principal vectors) or of the prevalence of dengue fever generally conclude there will be an increase in the number of mosquitos and a larger geographic range at 2° than at 1.5°C and beyond than at present, and suggest more individuals at risk of dengue fever, with regional differences (*high confidence*) (Fischer et al., 2011; Colón-González et al., 2013; Fischer et al., 2013; Bouzid et al., 2014; Ogden et al., 2014a; Mweya et al., 2016). The risks increase with greater warming. Projections suggest that climate change will expand the geographic range of chikungunya, with greater expansions with higher degrees of warming (Tjaden et al., 2017).

Other vector-borne diseases: Increased warming in North America and Europe could result in latitudinal and altitudinal expansions of regions climatically suitable for West Nile Virus transmission, particularly along the current edges of its transmission areas, and extension of the transmission season, with the magnitude and pattern of changes varying by location and degree of warming (Semenza et al., 2016). Most projections conclude that climate change will expand the geographic range and seasonality of Lyme and other tick-borne diseases in parts of North America and Europe (Ogden et al., 2014b; Levi et al., 2015). The changes are larger with greater warming and under higher greenhouse gas emission pathways. Projections of the impacts of climate change on leishmaniosis and Chagas disease indicate climate change could increase or decrease future health burdens, with greater impacts at higher degrees of warming (González et al., 2014; Ceccarelli and Rabinovich, 2015).

In summary, warming of 2°C poses greater risks to human health than warming of 1.5°C, often with the risks varying regionally, and with a few exceptions (*high confidence*). There is *very high confidence* that each additional unit of warming will increase heat-related morbidity and mortality, and that adaptation would reduce the magnitude of impacts. There is *high confidence* that ozone-related mortality will increase if precursor emissions remain the same, and that warmer temperatures will affect the transmission of some infectious diseases, with increases and decreases projected depending on disease (e.g., malaria, dengue, West Nile virus, and Lyme disease), region, and degree of temperature change.

3.4.8 Urban areas

There is new literature on urban climate change and its differential impacts on and risks for infrastructure sectors —energy, water, transport, buildings— and vulnerable populations, including those living in informal settlements (UCCRN, 2018). However, there is limited literature on the risks of warming of 1.5°C and 2°C in urban areas. Heat-related extreme events (Matthews et al., 2017), variability in precipitation (Yu et al., 2018) and sea-level rise can directly affect urban areas (Bader et al., 2018; Dawson, et al., 2018; Section 3.4.5). Indirect risks may arise from interactions between urbanization and natural systems.

Future warming and urban expansion could lead to more extreme heat stress (Argüeso et al., 2015; Suzuki-Parker et al., 2015). At 1.5°C, twice as many megacities (such as Lagos, Nigeria and Shanghai, China) could become heat-stressed, exposing more than 350 million more people to deadly heat by 2050 under midrange population growth. Without considering adaptation options, such as cooling from more reflective roofs, and overall characteristics of urban agglomerations in terms of landuse, zoning and building codes (UCCRN, 2018), at 2°C warming, Karachi (Pakistan) and Kolkata (India) could expect annual conditions equivalent to the deadly 2015 heatwaves (Akbari et al., 2009; Oleson et al., 2010; Matthews et al., 2017). Warming of 2°C is expected to increase the risks of heatwaves in China's urban agglomerations (Yu and Zhai, 2018). Stabilising at 1.5 °C warming could decrease extreme temperature-related mortality compared with stabilisation at 2°C for key European cities, assuming no adaptation and constant vulnerability (Jacob et al., 2018; Mitchell et al., 2018). Holding temperature change to below 2°C, taking Urban Heat Islands (UHI) into consideration, could result in a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, with both substantially larger than under the present climate (Matthews et al., 2017; Yu et al., 2018).

For extreme heat events, an additional 0.5°C of warming implies a shift from the upper-bounds of observed natural variability to a new global climate regime (Schleussner et al., 2016b), with differential implications for the urban poor (Revi et al., 2014; Jean-Baptiste et al., 2018; UCCRN, 2018). Adverse impacts of extreme events could arise in tropical coastal areas of Africa, South America, and South East Asia (Schleussner et al., 2016b), with large informal settlements and other vulnerable urban populations, and with vulnerable assets, including urban infrastructure—energy, water, transport, and buildings (McGranahan et al., 2007; Hallegatte et al., 2013; Revi et al., 2014; UCCRN, 2018). Mediterranean water stress is projected to increase from 9% at 1.5°C to 17% at 2°C compared to 1986-2005. Regional dry spells are projected to expand from 7% at 1.5°C to 11% at 2°C. Sea-level rise is expected to be lower for 1.5°C than 2°C, lowering risks for coastal metropolitan agglomerations (Schleussner et al., 2016b).

Increases in the intensity of UHI could exacerbate warming of urban areas, with projections ranging from a 6% decrease to a 30% increase for a doubling of CO_2 (McCarthy et al., 2010). Increases in population and city size, in the context of a warmer climate, are projected to increase UHI (Georgescu et al., 2012; Argüeso et al., 2014; Conlon et al., 2016; Kusaka et al., 2016; Grossman-Clarke et al., 2017).

Climate models are better at projecting implications of greenhouse gas forcing on physical systems than assessing differential risks associated with achieving a specific temperature target (James et al., 2017). These challenges in managing risks are amplified when combined with the scale of urban areas and assumptions about socio-economic pathways (Krey et al., 2012; Kamei et al., 2016; Yu et al., 2016; Jiang and Neill, 2017).

In summary, in the absence of adaptation, in most cases, warming of 2°C poses greater risks to urban areas than warming of 1.5°C, depending on the vulnerability of the location (coastal or non-coastal), infrastructure sectors (energy, water, transport), levels of poverty and the mix of formal and informal settlements.

3.4.9 Key economic sectors and services

Climate change will affect tourism, energy systems, and transportation through direct impacts on operations (e.g., sea level rise) and through impacts on supply and demand, with the risks varying significantly across geographic region, season, and time. Projected risks also depend on assumptions with respect to population growth, the rate and pattern of urbanization, and investments in infrastructure. Table S10 in Annex 3.1 summarizes the cited publications.

3.4.9.1 Tourism

The implications of climate change for the global tourism sector are far-reaching and are impacting sector investments, destination assets (environment and cultural), operational and transportation costs, and tourist demand patterns (Scott et al., 2016a; Scott and Gössling, 2018). Since the AR5, observed impacts on tourism markets and destination communities continue to be not well analyzed, despite many analogue conditions (e.g., heatwaves, major hurricanes, wild fires, reduced snow pack, coastal erosion, coral reef bleaching) that are anticipated to occur more frequently with climate change. There is some evidence that observed impacts on tourism assets (environmental and cultural heritage) is leading to the development of 'last chance' tourism markets, where travellers visit destinations before they are substantially degraded by climate change impacts or to view the impacts of climate change on landscapes (Lemelin et al., 2012; Stewart et al., 2016; Piggott-McKellar and McNamara, 2017).

There is limited research on the differential risks of 1.5° versus 2°C temperature increase and resultant environmental and socio-economic impacts in the tourism sector. The translation of these changes in climate resources for tourism into projections of tourism demand remains geographically limited to Europe. Based on analyses of tourist comfort, summer and spring-autumn tourism in much of Western Europe may be favored by 1.5°C warming, with negative effects projected for Spain, Cyprus (decrease of 8% and 2% overnight stays, respectively) and most coastal regions of the Mediterranean (Jacob et al., 2018). Similar geography of potential tourism gains (central and northern Europe) and reduced summer favorability (Mediterranean countries) are projected under 2°C (Grillakis et al., 2016). Considering potential changes in natural snow only, winter overnight stays at 1.5°C are projected to decline by 1–2% in Austria, Italy, and Slovakia, with an additional 1.9 million overnight stays lost under 2°C warming (Jacob et al., 2018). Using an econometric analysis of the relationship between regional tourism demand and climate conditions, Ciscar et al. (2014) projected a 2°C world would reduce European tourism by -5% (€15 billion yr^{-1}), with losses up to -11% (€6 billion yr-1) for southern Europe and a potential gain of €0.5 billion yr^{-1} in the UK.

Growing evidence indicates that the magnitude of projected impacts is temperature-dependent and sector risks will be much greater with higher temperature increases and resultant environmental and socio-economic impacts (Markham et al., 2016; Scott et al., 2016a; Jones, 2017; Steiger et al., 2017). Studies from 27 countries consistently project substantially decreased reliability of ski areas that are dependent on natural snow, increased snowmaking requirements and investment in snowmaking systems, shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered competitiveness among and within regional ski markets, and subsequent impacts on employment and the value of vacation properties (Steiger et al., 2017). Studies that continue to omit snowmaking do not reflect the operating realities of most ski areas and overestimate impacts at 1.5–2°C. In all regional markets, the extent and timing of these impacts depend on the magnitude of climate change and the types of adaptive responses by the ski industry, skiers and destination communities. The decline in number of former Olympic Winter Games host locations that could remain climatically reliable for future Olympic and Paralympic Winter Games was also projected to be much greater under scenarios warmer than 2°C (Scott et al., 2015; Jacob et al., 2018).

The tourism sector is also affected by climate-induced changes in environmental systems that are critical assets for tourism, including biodiversity, beaches, glaciers, and other environmental and cultural heritage. Limited analyses of projected risks associated with 1.5° versus 2°C are available (Section 3.4.4.12). A global analysis of SLR risk to 720 UNESCO Cultural World Heritage sites projected that about 47 sites could be affected under 1°C warming, increasing to 110 and 136 sites under 2°C and 3°C, respectively (Marzeion and Levermann, 2014). Similar risks to vast worldwide coastal tourism infrastructure and beach assets remain unquantified in most major tourism destinations and SIDS that economically depend on coastal tourism. One exception is the projection that an eventual 1 m SLR could partially or fully inundate 29% of 900 coastal resorts in 19 Caribbean countries, with a substantially higher proportion (49–60%) vulnerable to associated coastal erosion (Scott and Verkoeyen, 2017).

A major barrier to understanding the risks of climate change for tourism (from the destination community to global scales) has been the lack of integrated sectoral assessments that analyze the full range of potential compounding impacts and their interactions with other major drivers of tourism (Rosselló-Nadal, 2014; Scott et al., 2016b). A global vulnerability index (27 indicators) in 181 countries found that countries with the lowest risk are found in western and northern Europe, central Asia, Canada, and New Zealand, while the highest sector risks are projected in Africa, the Middle East, South Asia, and SIDS in the Caribbean, Indian and Pacific Oceans (Scott and Gössling, 2018). Countries with the highest risks and where tourism represents a significant proportion of the national economy (more than 15% GDP) include many SIDS and least developed countries. Sectoral climate change risk also aligned strongly with regions where tourism growth is projected to be the strongest over the coming decades, including sub-Saharan Africa and South Asia; representing an important potential barrier to tourism development. The transnational implications of these impacts on the highly interconnected global tourism sector and the contribution of tourism to achieving the 2030 Sustainable Development Goals (SDGs) remain important uncertainties.

In summary, climate is an important factor influencing the geography and seasonality of tourism demand and spending globally (*very high confidence*). Increasing temperatures will directly impact climate dependent tourism markets, including sun and beach, and snow sports tourism, with lesser risks for other tourism markets that are less climate sensitive (*high confidence*). The degradation or loss of beach and coral reef assets will increase risks for coastal tourism, particularly in sub-tropical and tropical regions (*high confidence*).

3.4.9.2 Energy systems

Climate change will likely increase the demand for air conditioning in most tropical and sub-tropical regions (Arent et al., 2014; Hong and Kim, 2015). Increasing temperatures will decrease the thermal efficiency of fossil, nuclear, biomass and solar power generation technologies, as well as buildings and other infrastructure (Arent et al., 2014). For example, in Ethiopia, capital expenditures through 2050 might either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario (Block and Strzepek, 2012). In the Zambezi River basin, hydropower may fall by 10% by 2030 (about 1.5°C) and by 35% by 2050 under the driest scenario (Strzepek et al., 2012).

Impacts on energy systems can affect Gross Domestic Product (GDP). The economic damage in the United States from climate change is estimated to be roughly 1.2% cost of GDP per 1°C increase on average under RCP8.5 (Hsiang et al., 2017). Projections of the GDP indicate that negative impacts of energy demand associated with space heating and cooling in 2100 are highest (median: –0.94%) under 4°C (RCP8.5) compared with a GDP change (median: –0.05%) under 1.5°C, depending on the socio-economic conditions (Park et al., 2018). Additionally, total energy demands for heating and cooling at the global scale do not change much with increases in Global Mean Temperature (GMT) up to 2°C. There is, however, a high degree of variability between regions (Arnell et al., 2018).

Evidence for the impact of climate change on energy systems since AR5 is limited. Globally, gross hydropower potential is projected to increase (+2.4% under RCP2.6; +6.3% under RCP8.5 for the 2080s) with the most growth in central Africa, Asia, India, and northern high latitudes (van Vliet et al., 2016). Byers et al. (2018) found energy impacts at 2ºC increase including increased cooling degree days, especially in tropical regions, as well as increased hydro-climatic risk to thermal and hydropower plants predominantly in Europe, North America, south and southeast Asia, and southeast Brazil. Donk et al. (2018) assessed future climate impacts on hydropower in Suriname, finding a decrease of approximately 40% power capacity is projected for global temperature increase in the range of 1.5°C. At minimum and maximum increases in global mean temperatures of 1.35° and 2°C, the overall stream flow in Florida, USA is projected to increase by an average of 21% with pronounced seasonal variations, resulting in increases in power generation in winter (72%) and autumn (15%) and decreases in summer (–14%; Chilkoti et al., 2017). Changes are greater at the higher projected temperature. In a reference scenario with global mean temperatures rising by 1.7°C from 2005 to 2050, U.S. electricity demand in 2050 was 1.6–6.5% higher than a control scenario with constant temperatures (McFarland et al., 2015). Decreased electricity generation of –15% is projected for Brazil starting in 2040, declining to –28% later in the century (de Queiroz et al., 2016). In large parts of Europe, electricity demand is projected to decrease mainly due to reduced heating demand (Jacob et al., 2018).

In Europe, no major differences in large-scale wind energy resources, inter-annual or intra-annual variability are projected for 2016–2035 under RCP8.5 and RCP4.5 (Carvalho et al., 2017). However, in 2046–2100, wind energy density is projected to decrease in Eastern Europe and increase in Baltic regions (–30% vs. +30%). Intra-annual variability is expected to increase in Northern Europe and decrease in Southern Europe. Under RCP4.5 and RCP8.5, the annual energy yield of European wind farms as a whole as projected to be installed by 2050 will remain stable (±5 for all climate models). However, wind farm yields will undergo changes up to 15% in magnitude at country and local scales and a 5% change in magnitude at regional scale (Tobin et al., 2015, 2016). Hosking et al. (2018) assessed wind power generation over Europe for 1.5°C warming, finding the potential for wind energy to be greater than previously assumed in Northern Europe. Additionally, Tobin et al. (2018) assessed impacts under 1.5°C and 2°C increases on wind, solar photovoltaic and thermoelectric power generation across Europe. Results found that photovoltaic and wind power might be reduced by up to 10%, and hydropower and thermoelectric generation might decrease by up to 20%, with limited impacts for 1.5°C warming, but increasing as temperature increases (Tobin et al., 2018).

3.4.9.3 Transportation

Road, air, rail, shipping and pipeline transportation can be impacted directly or indirectly by weather and climate, including increases in precipitation and temperature; extreme weather events (flooding and storms); SLR; and incidence of freeze-thaw cycles (Arent et al., 2014). Much of the published research on the risks of climate change for the transportation sector has been qualitative.

Limited new research since the AR5 supports that increases in global temperatures will impact the transportation sector. Warming is projected to result in increased numbers of days of ice-free navigation and a longer shipping season in cold regions, thus impacting shipping and reducing transportation cost (Arent et al., 2014). In the North Sea Route, large-scale commercial shipping might not be possible until 2030 for bulk shipping and until 2050 for container shipping under RCP8.5, but more shipping resulting in short-lived pollutants, as well as CO_2 and non-CO_2 emissions associated with additional economic growth enabled by the North Sea Route, is expected to contribute to a mean temperature rise of 0.05% (Yumashev et al., 2017). For a scenario with global mean temperature stabilization of open water vessel transits has the potential to double by mid-century with a season ranging from two to four months (Melia et al., 2016).

3.4.10 Livelihoods and poverty, and the changing structure of communities

Multiple drivers and embedded social processes influence the magnitude and pattern of livelihoods and poverty, and the changing structure of communities related to migration, displacement, and conflict (Adger et al., 2014). In AR5, evidence of a climate change signal was limited, with more evidence of impacts of climate change on the places where indigenous people live and on traditional ecological knowledge (Olsson et al., 2014).

3.4.10.1 Livelihoods and poverty

At approximately 1.5°C (2030), climate change will be a poverty-multiplier that makes poor people poorer, and increases the poverty head count (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Poor people might be heavily affected by climate change even when impacts on the rest of population are limited. Climate change could force more than 100 million people into extreme poverty, with the numbers attributed to climate change alone between 3 million and 16 million, mostly through impacts on agriculture and food prices (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Unmitigated warming could reshape the global economy later in the century by reducing average global incomes and widening global income inequality (Burke et al., 2015b). Most severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia.

3.4.10.2 The changing structure of communities: Migration, displacement, and conflict

Migration: In AR5,the potential impacts of climate change on migration and displacement were identified as an emerging risk (Oppenheimer et al., 2014). The social, economic and environmental factors underlying migration are complex and varied; therefore, detecting the effect of observed climate change or assessing its possible magnitude is challenging with any degree of confidence (Cramer et al., 2014).

No studies specifically explored the difference in risks between 1.5ºC and 2ºC on human migration. The literature consistently highlights the complexity of migration decisions and the difficulties in attributing causation (e.g. (Nicholson, 2014; Baldwin and Fornalé, 2017; Bettini, 2017; Constable, 2017; Islam and Shamsuddoha, 2017; Suckall et al., 2017). The studies on migration that most closely explore the probable impacts of 1.5ºC and 2ºC typically focus on the effects of temperature and precipitation anomalies directly on migration or indirectly through examining migration due to changing agriculture yield and livelihood sources (Mueller et al., 2014; Piguet and Laczko, 2014; Mastrorillo et al., 2016; Sudmeier-Rieux et al., 2017).

Temperature had a positive and statistically significant effect on outmigration over recent decades in 163 countries, but only for agricultural-dependent countries (R. Cai et al., 2016). A 1°C increase in temperature in the International Migration Database of the Organisation for Economic Co-operation and Development (OECD) was associated with a 1.9% increase in bilateral migration flows from 142 sending countries and 19 receiving countries, and an additional millimeter of precipitation was associated with an increase in migration by 0.5% (Backhaus et al., 2015). An increase in precipitation anomalies, but over a different time period, was strongly associated with an increase in outmigration but no significant effects of temperature anomalies were reported (Coniglio and Pesce, 2015).

Internal and international migration have always been important for small islands (Farbotko and Lazrus, 2012; Weir et al., 2017). There is rarely a single cause for migration (Constable, 2017). Numerous factors are important, including work, education, quality of life, family ties, access to resources or development (Bedarff and Jakobeit, 2017; Speelman et al., 2017; Nicholls et al., 2018). Depending on the situation, changing weather, climatic, or environmental conditions might each be one factor in the choice to migrate (Campbell and Warrick, 2014).

Displacement: At 2°C warming, there is a potential for significant population displacement concentrated in the tropics (Hsiang and Sobel, 2016). Tropical populations may have to move at distances greater than 1000 km if global mean temperature rises by 2 °C from the period of 2011–2030 to the end of the century. A disproportionately rapid evacuation from the tropics could lead concentration of population in tropical margins and the subtropics, where population densities could increase by 300% or more (Hsiang and Sobel, 2016).

Conflict: A recent study has called for cautiousness in relating conflict to climate change due to sampling bias (Adams et al., 2018). Often taking limited consideration of the multiple drivers of conflict, inconsistent associations are reported between climate change and conflict (e.g., Hsiang et al., 2013; Hsiang and Burke, 2014; Buhaug, 2015, 2016; Carleton and Hsiang, 2016; Carleton et al., 2016). There also are inconsistent relationships between climate change, migration, and conflict (e.g., Theisen et al., 2013; Buhaug et al., 2014; Selby, 2014; Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Christiansen, 2016; Reyer et al., 2017c; Waha et al., 2017). Across world regions and the international to micro level, the strength of the relationship between drought and conflict under most circumstances is limited (Buhaug, 2016; von Uexkull et al., 2016). However, drought significantly increases the likelihood of sustained conflict for particularly vulnerable nations or groups due to their livelihood dependance on agriculture. This is particularly relevant among groups in the least developed countries (von Uexkull et al., 2016), sub-Saharan Africa (Serdeczny et al., 2016; Almer et al., 2017) and in the Middle East (Waha et al., 2017). Hsiang et al. (2013) report causal evidence and convergence across studies that climate change is linked to human conflicts across all major regions of the world, and across a range of spatial and temporal scales. A 1°C increase in temperature or more extreme rainfall increases the frequency of intergroup conflicts by 14% (Hsiang et al., 2013). If the world warms by 2˚C–4˚C by 2050, then rates of human conflict could increase. Some causal associations between violent conflict and socio-political stability were reported from local to global scales and from hours to millennium (Hsiang and Burke, 2014). A temperature increase by one standard deviation in increased the risk of interpersonal conflict by 2.4% and intergroup conflict by 11.3% (Burke et al., 2015a). Armed-conflict risks and climate-related disasters are associated in ethnically fractionalized countries, indicating there is no clear signal that environmental disasters directly trigger armed conflicts (Schleussner et al., 2016a).

In summary, average global temperatures that extend beyond 1.5ºC are likely to increase poverty and disadvantage in many populations globally. By the mid to late 21st century, climate change is projected to be a poverty multiplier that makes poor people poorer and increases poverty head count, and the association of temperature and economic productivity is not linear (*high confidence*). Temperature has a positive and statistically significant effect on outmigration for agricultural-dependent communities (*medium confidence*).

3.4.11 Interacting and cascading risks

The literature on compound as well as interacting and cascading risks at warming of 1.5°C and 2°C is limited. Spatially compound risks, often referred to as hotspots, involve multiple hazards from different sectors overlapping in location (Piontek et al., 2014). Global exposures were assessed for 14 impact indicators covering water, energy and land sectors from changes including drought intensity and water stress index, cooling demand change and heatwave exposure, habitat degradation, and crop yields using an ensemble of climate and impact models (Byers et al., 2018). Exposures approximately double between 1.5°C and 2°C, and the land area affected by climate risks increases as warming progresses. For populations vulnerable to poverty, the exposure to climate risks in multiple sectors is an order of magnitude greater (8–32 fold) in the high poverty and inequality scenarios (SSP3; 765–1,220 million) compared to sustainable socioeconomic development (SSP1; 23–85 million). Asian and African regions are projected to experience 85–95% of global exposure with 91–98% of the exposed and vulnerable population (depending on SSP/GMT combination), approximately half of which are in South Asia. Figure 3.18 shows that moderate and high multi-sector impacts are prevalent where vulnerable people live, predominantly in South Asia (mostly Pakistan, India, and China), at 1.5°C, but spreading to sub-Saharan Africa, the Middle East, and East Asia at higher levels of warming. Beyond 2°C and at higher risk thresholds, the world's poorest are expected to be disproportionately impacted, particularly in cases (SSP3) of high inequality in Africa and southern Asia. Table 3.4 shows the number of exposed and vulnerable people at 1.5°C and 2°C, with 3°C for context, for selected multi-sector risks.

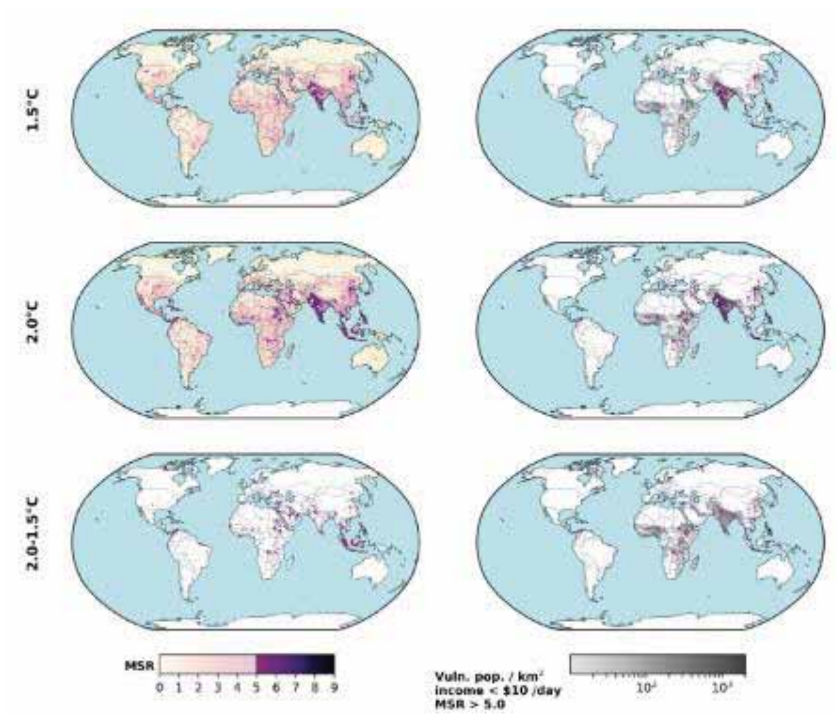

Figure 3.18: Multi-sector risk maps for 1.5, 2°C, and locations where 2°C brings impacts not experienced at 1.5°C (2–1.5°C). The left column shows the full range of the multi-sector risk score (range 0–9) with transparency and the scores >5.0 in full color. Score must be >4.0 to be considered "multi-sector". The right column

greyscale overlays the 2050 vulnerable populations (low income) under Shared Socioeconomic Pathway (SSP)2 with the multi-sector risk score > 5.0 in full color, indicating the concentrations of exposed and vulnerable populations to risks in multiple sectors. Source: (Byers et al., 2018)

Table 3.4: Number of exposed and vulnerable people at 1.5°C, 2°C, and 3°C for selected multi-sector risks under Shared Socioeconomic Pathways (SSPs). Source: (Byers et al., 2018)

SSP2 (SSP1 to SSP3 range), millions	**1.5°C**		**2°C**		**3°C**	
Indicator	Exposed	Exposed & Vulnerable	Exposed	Exposed & Vulnerable	Exposed	Exposed & Vulnerable
Water stress index	3340 (3032-3584)	496 (103-1159)	3658 (3080-3969)	586 (115-1347)	3920 (3202-4271)	662 (146-1480)
Heatwave event exposure	3960 (3546-4508)	1187 (410-2372)	5986 (5417-6710)	1581 (506-3218)	7909 (7286-8640)	1707 (537-3575)
Hydroclimate risk to power production	334 (326-337)	30 (6-76)	385 (374-389)	38 (9-94)	742 (725-739)	72 (16-177)
Crop yield change	35 (32-36)	8 (2-20)	362 (330-396)	81 (24-178)	1817 (1666-1992)	406 (118-854)
Habitat degradation	91 (92-112)	10 (4-31)	680 (314-706)	102 (23-234)	1357 (809-1501)	248 (75-572)
Multi-sector exposure	Summarise					
2 indicators	1129 (1019 – 1250)	203 (42 – 487)	2726 (2132 – 2945)	562 (117 – 1220)	3500 (3212 – 3864)	707 (212 – 1545)
3 indicators	66 (66 – 68)	7 (0.9 – 19)	422 (297 – 447)	54 (8 – 138)	1472 (1177 – 1574)	237 (48 – 538)
4 indicators	5 (0.3 – 5.7)	0.3 (0 – 1.2)	11 (5 – 14)	0.5 (0 – 2)	258 (104 – 280)	33 (4 – 86)

3.4.12 Summary of projected risks at 1.5°C and 2°C of global warming

The following table summarises the information presented as part of Section 3.4, illustrating the growing of evidence of increasing risks across a broad range of natural and human systems at 1.5°C and 2°C of global warming.

Table 3.5: Summary of projected risks at 1.5ºC and 2ºC of global warming

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
Freshwater	Precipitation, temperature, snowmelt	Water Stress	Additional 8% of the world population in 2000 to new or aggravated water scarcity	Around half compared to the risks at 2.0ºC	~100% increase	M		Europe, Australia and southern Africa		3	L	L	M
		Fluvial flood	170% increase in population affected as compared to the impact simulated over the baseline	100% increase in population affected as compared to the impact simulated over the	70% increase	M	U.S., Asia, and Europe		Africa and Oceania	2	L/M	L/M	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
			period 1976–2005	baseline period 1976–2005									
		Drought	410.7±213.5 million, changes in urban population exposure to severe drought at the globe	350.2±158.8 million, changes in urban population exposure to severe drought at the globe	60.5±84.1 million (±84.1 based on the SSP1 scenario)	M	Central Europe, Southern Europe, the Mediterranean, West Africa, East and West Asia and Southeast Asia			2	L/M	L/M	L
Terrestrial ecosystems	Temperature, precipitation	Species range loss	H (18% insects, 8% vertebrates, 16% plants lose >50% range)	M (6% insects, 4% vertebrates, 8% plants, lose >50% range)	Double or triple	H		Amazon, Europe, South Africa		1, 4	M	L	H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Loss of ecosystem functioning and services	H	M		M							
		Shifts of biomes (major ecosystem types)	13% (range 8–20%) transformed	Around 7% transformed	Around double	H		Arctic, Tibet, Himalayas, South Africa and Australia		4	-	-	-
	Heat and cold stress, warming, precipitation	Wildfire	H	H	L	M	Canada, USA, Mediterranean	Mediterranean	Central and South America, Australia, Russia, China, Africa	1, 2, 4, 5	L	L	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
Ocean	Warming and stratification of the surface ocean	Loss of framework species (coral reefs)	very H (*virtually certain*)	H	3	H/very H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; deep water coral reefs	1, 2	H	L	H
		Loss of framework species (seagrass)	H	M	5	H/very H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; Myanma	1, 2	M	L	M/H
		Loss of framework species (mangroves)	M/H	M	3	M/H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; Myanmar	1, 3	M	L	M/H
		Disruption of marine food webs	M	L	5	M	Global	Global	Deep Sea	4	M	L	M/H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Range migration of marine species and ecosystems	H	M	5	H	Global	Global	Deep Sea	1	M	L	H
		Loss of finfish and fisheries	M/H	M/H	5	H	Global	Global	Deep Sea	4	M	M/L	M/H
	Ocean acidification and elevated sea temperatures	Loss of coastal ecosystems and protection	M	L/M	5	M	Low latitude tropical/subtropical countries	Low latitude tropical/subtropical countries	Most regions - risks not well defined	1	M	M/L	M
		Loss of bivalves and bivalve fisheries	M	M	3	H	Temperate countries with up-welling	Temperate countries with up-welling	Most regions - risks not well defined	4	M/H	L/M	M/H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Changes to physiology and ecology of marine species	M	L/M	3	H	Global	Global	Most regions - risks not well defined	4	L	L	M/H
	Reduced bulk ocean circulation and de-oxygenation	Increased hypoxic dead zones	L/M	L	5	L/M	Temperate countries with up-welling	Temperate countries with up-welling	Deep Sea	4	L	L	M
		Changes to up-welling productivity	M	L	5	L/M	Most upwelling regions	Most upwelling regions	Some up-welling systems	4	L	L	M
	Intensified storm	Loss of coastal ecosystems	H/very H	H	5	H	Tropical/subtropical countries	Tropical/subtropical countries		1, 4	M	L	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Inundation and destruction of human/coastal infrastructure and livelhoods.	H/very H	H	5	H	Global	Global		1, 5	M/H	M	M/L
	Loss of sea ice	Loss of habitat	very H	H	5	H	Polar regions	Polar regions		1	L	very L	H
		Increased productivity but changing fisheries	M/H	L/M	5	very H	Polar regions	Polar regions		1, 4	L	M/L	H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
Coastal	Sea level rise, increased storminess	Area exposed (assuming no defences)	590-613 th km^2 when 2.0degC first reached	562-575 th km^2 when 1.5degC first reached	Increasing . 25 -38 th km^2 when temperatures are first reached, 10-17 th km^2 in 2100 increasing to 16-230 th km^2 in 2300	M/H (dependent on population datasets)	Asia. Small islands	Asia. Small islands	Small islands	2,3	M	M	M
		Population exposed (assuming no defences)	141-151 million when 2.0degC first reached	128-143 million when 1.5degC first reached	Increasing . 13 - 8 million when temperatures are first reached, 0-6 million people in	M/H (dependent on population datasets)	Asia. Small islands	Asia. Small islands	Small islands	2,3	M	M	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
					2100, increasing to 35-95 million people in 2300								
		People at risk taking account of defences (modelled in 1995)	Between 14.9-52.3 million people / yr if defences are not upgraded from the modelled 1995 baseline	Between 2.3-27.8 million people / yr as defences are not upgraded from the 1995 baseline	Increasing with time, but highly dependent on adaptation.	M/H (dependent on adaptation)	Asia. Small islands. Potentially African nations.	Asia. Small islands	Small islands	2,3, 4	M	M	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
Food security and food production systems	Heat and cold stress, warming, precipitation	Changes in ecosystem production	H	M/H	M/H	M/H	Global	Noth America, Central and South America, Mediterranean basin, South Africa, Australia, Asia	- - -	2, 4,5	H	M/H	M/H
	Heat and cold stress, warming, precipitation	Shift and composition change of biomes (major ecosystem types)	H	M/H	M	L/M	Global	Global, Tropical areas, Mediterranean	Africa, Asia	1, 2, 3, 4	L/M	L	L/M
Human health	Temperature	Heat-related morbidity and mortality	M/H	M	Risk increased	VH	All regions at risk	All regions	Africa	2,3, 4	H	H	H
		Occupational heat stress	M/H	M	Risk increased	M	Tropical regions	Tropical regions	Africa	2,3, 4	H	M	M

Secto r	Physic al climat e change driver s	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confiden ce in risk statement s	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no informati on	RF C *	Adaptati on potential at 1.5ºC	Adaptati on potential at 2ºC	Confiden ce in assigning adaptatio n
	Air quality	Ozone-related mortality	M/H (if precursor emissions remain the same)	M (if precursor emissions remain the same)	Risk increased	H	High income and emerging economies	High income and emerging economies	Africa, parts of Asia	2,3, 4	L	L	M
	Temperatu re, precipitati	Undernutriti on	M/H	M	Risk increased	H	Low-income countries in Africa and Asia	Low-income countries in Africa and Asia	Small islands	2,3, 4	M	L	M
Key economic	Temperatu re	Tourism (sun and beach, and snow sports)	H	M/H	Risk increased	VH	Coastal tourism, particularly in sub-tropical and tropical regions	Coastal tourism, particularly in sub-tropical and tropical regions	Africa	1,2, 3	M	L	H

*RFC: 1 = unique and threatened systems, 2 = extreme events, 3 = unequal distribution of impacts, 4 = global aggregate impacts (economic + biodiversity), 5 = large scale singular events

3.4.13 Synthesis of key elements of risk

Some elements of the assessment in Section 3.4 are synthesised in a single diagram (Figure 3.19) that indicates the overall risk in five broad categories for natural and human systems as a result of anthropogenic climate change and increases in Global Mean Surface Temperature (GMST). The elements included are supported by a substantive enough body of literature providing at least *medium confidence* in the assessment. The format for figure 3.19 matches that of Figure 19.4 of WGII AR5 Chapter 19 (Oppenheimer et al., 2014) and Figure 3.19) by indicating the levels of the transition of risk from undetectable to moderate (detected and attributed), from moderate to high (severe and widespread) and from high to very high, the latter indicating significant irreversibility or persistence of climate-related hazards combined with a much reduced capacity to adapt. Regarding the transition from undetectable to moderate, the impact literature assessed in the AR5 focused on describing and quantifying linkages between weather and climate patterns and impact outcomes, with limited detection and attribution to anthropogenic climate change (Cramer et al., 2014). A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) confirmed that the impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of those related to precipitation is only weakly evident or absent. Moreover, there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016).

The current synthesis is complementary to the synthesis in Section 3.5.2 that categorizes risks into 'Reasons for Concern' (RFCs), as described in Oppenheimer et al. (2014). Each element presented here maps to one or more RFCs, and the figure indicates this relationship. It should be emphasized that risks to the issues assessed here are only a subset of the full range of risks that contribute to the RFCs. This figure is not intended to replace the RFCs but rather to indicate how risks to particular elements of the earth system accrue with global warming, with a focus on levels of warming of 1.5°C and 2°C. Key evidence assessed in earlier parts of this chapter are summarized to indicate the transition points between the levels of risk. A fuller account is in the Annex 3.1 S3-4-12.

In terrestrial ecosystems (related to RFC1 and RFC4), detection and attribution studies show that impacts of climate change on terrestrial ecosystems began to take place over the few decades, indicating a transition from no risk (white) to moderate risk (yellow) below recent temperatures (*high confidence*, Section 3.4.3). Risks to unique and threatened terrestrial ecosystems are generally higher under warming of 2°C as compared to 1.5°C (Section 3.5.2.1), while at the global scale, severe and widespread risks (red) are projected to occur by 2°C of warming. These risks are associated with biome shifts and species range loss (Sections 3.4.3 and 3.5.2.4); however, because many systems and species are unable to adapt to levels of warming below 2°C, the transition to high risk (red) is located below 2°C (*high confidence*). At 3°C of warming, however, biome shifts and species range losses escalate to very high levels and the systems have very little capacity to adapt (purple; Section 3.4.3; *high confidence*).

In the Arctic (related to RFC1), the increased rate of summer sea ice melt was detected and attributed to climate change by the year 2000 (corresponding to warming of 0.7°C), indicating moderate risk (yellow). At 1.5°C warming, an ice-free Arctic ocean is considered *unlikely* whilst by 2°C warming it is considered *likely* and this unique ecosystem is considered unable to adapt, hence a transition from high (red) to very high (purple) risk is expected between 1.5°C and 2°C warming.

For coral reefs, there is *high confidence* in the transitions between colour assignments, especially in the growing impacts in the transition of warming from 0.4°C to 0.6°C, and in projections of change from 0.6ºC to

1.3ºC (Section 3.4.4; Box 3.4). This assessment took into account the heat wave related loss of 50% of shallow water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef, as well as other sites globally. Together with sequential mass coral bleaching and mortality events on the Great Barrier Reef (Hoegh-Guldberg, 1999; Hughes et al., 2017b, 2018), suggest that climate risks are very high for coral reefs. General assessment of climate risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than climate change (Alongi, 2008; Gattuso et al., 2015)(Hoegh-Guldberg et al., 2014). Recent climate related die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that climate change risks may have been underestimated for mangroves as well, leading to risks considered to be undetectable to moderate, with the transition now starting at 1.3°C as opposed to 1.8ºC as assessed in 2015 (Gattuso et al., 2015). Risks of climate change related impacts on small-scale fisheries at low latitudes (many of which are dependent on ecosystems such as coral reefs and mangroves) *are moderate today but are expected to reach high levels of* risk by 1.1ºC (*high confidence*) (Section 3.4.4.10).

The transition from white to yellow (related to RFC3, 4) is based on AR5 WGII Chapter 7 which indicated with *high confidence* that climate change impacts on crop yields have been detected and attributed to climate change, with the current assessment providing further evidence to confirm this (Section 3.4.6). Impacts were detected in the tropics (AR5 WGII Chapter 7, AR5 WGII Chapter 18) and with increasing warming regional risks become high in some regions by 1.5°C warming, and in many regions by 2.5ºC warming, indicating a transition from moderate to high risk between 1.5ºC and 2.5°C warming (*medium confidence*). Impacts from fluvial flooding (related to RFCs 2, 3 and 4) depend on the frequency and intensity of the events as well as the extent of exposure and vulnerability of society (i.e., socioeconomic conditions; the effect of non-climate stressors). Risks posed by 1.5°C warming continue to increase with warming (Sections 3.4.2, 3.3.5), with projected increases threefold relative to current risk in economic damages due to flooding in 19 countries for a warming of 2°C, indicating a transition to high risk at this level (*medium confidence*). Because few studies assess the potential to adapt to these risks, there was insufficient evidence to locate a transition to very high risk (purple).

Climate-change induced SLR and associated coastal flooding (related to RFCs 2, 3 and 4) were detectable and attributable since approximately 1970 (Slangen et al., 2016), where temperatures have risen by 0.3°C (Section 3.3.9) (*medium confidence*). Analysis suggests that impacts could be more widespread in sensitive systems such as small islands (Section 3.4.5.3) (*high confidence*) and increasingly widespread by the 2070s (Brown et al., 2018a), even when considering adaptation measures, suggesting a transition to high risk (red) (Section 3.4.5). With 2.5°C warming, adaptation limits would be exceeded in sensitive areas, and hence a transition to purple (very high risk) can be located here (*medium confidence*). Sea level rise could have adverse effects for centuries, posing significant risk to low lying areas (Sections 3.4.5.7 and 3.5.2.5) (*high confidence*).

For heat-related morbidity and mortality (related to RFCs 2, 3 and 4), detection and attribution studies show heat-related mortality in some locations increased due to climate change (*high confidence*, Section 3.4.7, Ebi et al., 2017). The projected risks of heat-related morbidity and mortality are generally higher under warming of 2°C than 1.5°C (*high confidence*), with projections of greater exposure to high ambient temperatures and increased morbidity and mortality (Section 3.4.7). Risk levels will depend on the rate of warming and the (related) level of adaptation, so a transition in risk from moderate (yellow) to high (red) is located between 1ºC and 3°C with *medium confidence*.

For tourism (related to RFCs 3 and 4), changing weather patterns, extreme weather and climate events, and sea level rise are affecting many (but not all) global tourism investments and environmental and cultural destination assets (Section 3.4.4.12), with 'last chance' tourism markets developing based on observed impacts on environmental and cultural heritage (Section 3.4.9.1), indicating a transition from undetected to moderate risk between 0°C and 1.5°C (*high confidence*). Based on limited analyses, risks to the tourism sector are higher at 2°C than at 1.5°C, with greater impacts on climate-sensitive sun, beach, and snow sports tourism markets. The degradation or loss of coral reef systems will increase the risks to coastal tourism, particularly in sub-tropical and tropical regions. A transition in risk from moderate (yellow) to high (red) is located between 1.5 and 3°C (*medium confidence*).

Owing to the existing effects that climate change is already having upon ecosystems, human health and agriculture, climate change is already beginning to make it more difficult to reach goals to eradicate poverty and hunger and protect health and life on land (Sections 5.1 and 5.2.1), suggesting a transition from undetected to moderate risk below recent temperatures at 0.5°C warming *(medium confidence).* Based on limited analyses there is evidence and agreement that the risks to sustainable development are considerably less at 1.5°C than 2°C (Section 5.2.2) including avoided impacts on poverty and food security. It is easier to achieve many of the Sustainable Development Goals (SDGs) at 1.5°C, suggesting that a transition to higher risk has not yet begin at this level. At 2°C and higher (e.g., RCP8.5) however, there are high risks of failure to meet SDGs such as eradicating poverty and hunger, providing safe water, reducing inequality, and protecting ecosystems and which are likely to become severe and widespread if warming were increase further to about 3°C *(medium confidence)* (Section 5.2.3).

Disclosure statement: The selection of elements is not intended to be fully comprehensive and does not necessarily include all elements for which there is a substantive body of literature, nor does it necessarily include all elements which are of particular interest to decision makers.

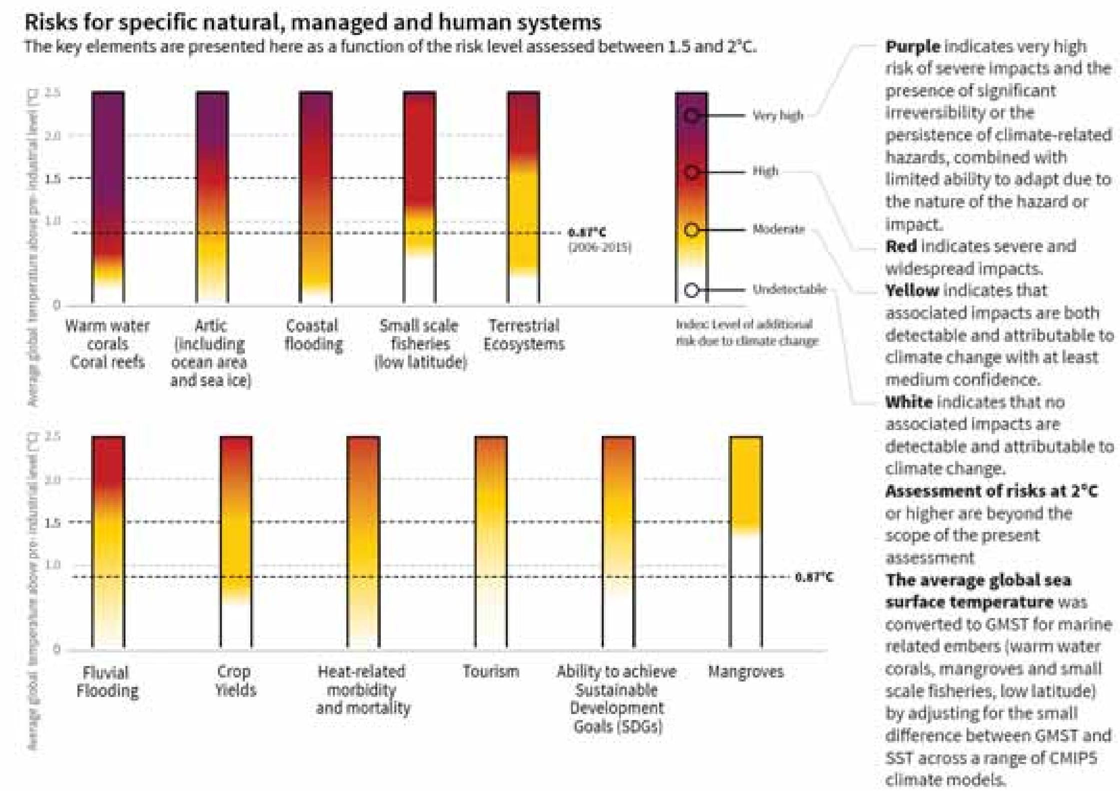

Figure 3.19 The dependence of risk associated with selected elements of human and natural systems on the level of climate change, adapted from Figure 3.18 and from AR5 WGII Chapter 19, and highlighting the nature of this dependence between 0 and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual 'element'. At one end, undetectable risk (white) indicates no detection and attribution of climate change with at least medium confidence. At the other end of the risk spectrum, the transition from red to purple, introduced for the first time in AR4, is defined by very high risk and the presence of significant irreversibility or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across elements indicates the relative sensitivity of elements to increases in Global Mean Surface Temperature (GMST). As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation independently of development pathway. The levels of risk illustrated reflect the judgements of the authors of Chapter 3 and Gattuso et al. (2015; for three marine elements).

3.5 Avoided impacts and reduced risks at 1.5ºC compared with 2ºC

3.5.1 Introduction

Oppenheimer et al. (2014, AR5 Chapter 19) provide a framework that aggregates projected risks from global mean temperature change into five categories known as 'Reasons for Concern'. Risks are classified as moderate, high, or very high and coloured yellow, red and purple respectively in Figure 19.4 (see AR5 Chapter 19 for details and findings). The framework's conceptual basis and the risk judgments made in Oppenheimer et al. (2014) were recently reviewed, confirming most judgements made in the light of more recent literature (O'Neill et al., 2017). We adopt the approach of Oppenheimer et al. (2014), with updates in terms of the aggregation of risk as informed by the most recent literature, for the analysis of avoided impacts at 1.5°C compared to 2°C of global warming presented in this section.

The economic benefits to be obtained by achieving the global temperature goal of 1.5°C, as compared to 2°C (or higher) are discussed in Section 3.5.3 in the light of the five reasons for concern explored in Section 3.5.2. Climate change hot spots that can be avoided or reduced by achieving the 1.5°C target are summarised in Section 3.5.4. The section concludes with a discussion of regional tipping points that can be avoided at 1.5ºC compared to higher degrees of global warming (Section 3.5.5).

3.5.2 Aggregated avoided impacts and reduced risks at 1.5°C versus 2°C of global warming

A brief summary of the accrual of RFC with global warming as assessed in WGII AR5 is provided in the following sections, which leads into an update of relevant literature published since AR5. The new literature is used to confirm the levels of global warming at which risks are considered to increase to moderate, and from moderate to high, and from high to very high. Figure 3.20 modifies Figure 19.4 from AR5 WGII with the ensuing text in this subsection providing the justification for the modifications. O'Neill et al. (2017) presents a very similar assessment to WGII AR%, but with further discussion of the future potential to create socioeconomic-scenario specific embers. At present, there is insufficient literature to do this so the original simple approach has been used here. Since the focus in the present assessment is on the consequences of warming of 1.5ºC to 2°C, no assessment for global warming of 3°C or more are included, and the embers developed here are discontinued at 2.5°C.

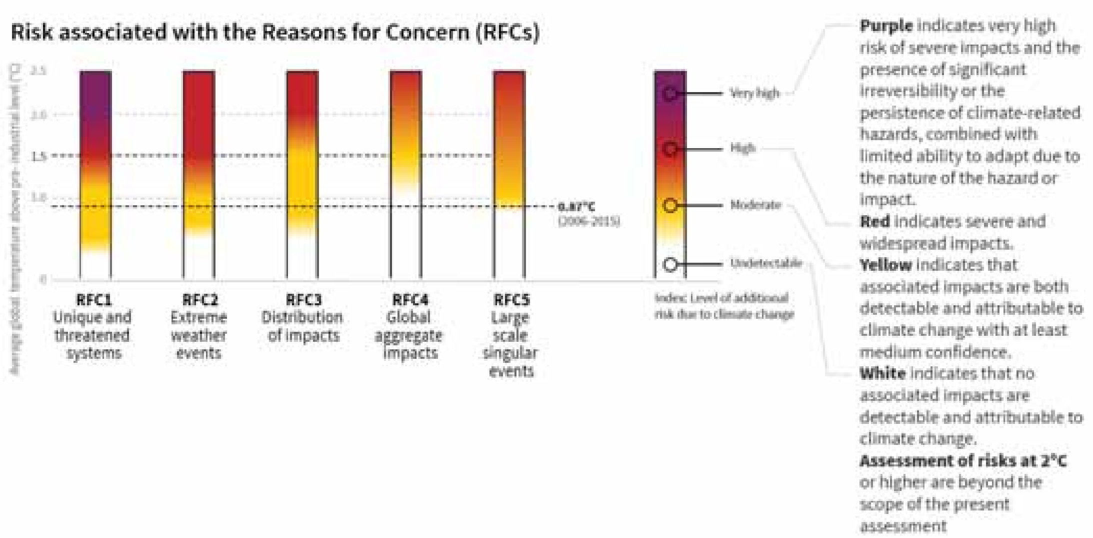

Figure 3.20: The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated and adapted from WGII AR5 Ch 19, Figure 19.4 and highlighting the nature of this dependence between 0ºC and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual 'reason'. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk and the presence of significant irreversibility or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. [Note to reviewers: In WGII AR5 Ch 19 and more recently in O'Neill et al. 2017 the need to detail how these kinds of figures vary with socioeconomic pathway is noted and suggestions are made therein as to how this might be done. That is seen as a task for IPCC AR6, and beyond the scope of what is feasible to do for SR1.5]

3.5.2.1 RFC 1- Unique and threatened systems

WGII AR5 Chapter 19 found that some unique and threatened systems are at risk from climate change at current temperatures, with increasing numbers of systems at risk of severe consequences at global warming of 1.6ºC above pre-industrial levels. It was also observed that many species and ecosystems have limited ability to adapt to the very large risks associated with warming of 2.6ºC or more, particularly Arctic sea ice and coral reef systems (*high confidence*). A transition from white to yellow indicating the onset of moderate risk was therefore located below present day global temperatures (*medium confidence*); a transition from yellow to red indicating the onset of high risk was located at 1.6ºC, and a transition to purple indicating the onset of very high risk at about 2.6ºC. This WGII AR5 analysis already implies a significant reduction in risks to unique and threatened systems if warming is limited to 1.5ºC as compared with 2ºC. Since AR5, evidence of present day impacts in these systems has continued to grow (Sections 3.4.2.2, 3.4.2.3, and 3.4.2.5), whilst new evidence has also accumulated about increased risks at 1.5ºC vs 2˚C warming in Arctic ecosystems (Section 3.3.9), coral reefs (Section 3.4.3), some other unique ecosystems (Section 3.4.2) and biodiversity.

New literature since AR5 provides a closer focus on the comparative levels of risk to coral reefs at 1.5ºC versus 2ºC global warming. As assessed in Section 3.4.4 and Box 3.4, reaching 2ºC will increase the frequency of mass coral bleaching and mortality to a point at which it will result in the total loss of coral reefs from the world's tropical and subtropical regions. Restricting overall warming to 1.5ºC will still see a downward trend in average coral cover (70–90% decline by mid-century) but will prevent the total loss of coral reefs projected with warming of 2˚C. The remaining reefs at 1.5˚C will also benefit from increasingly stable ocean conditions by the mid-to-late 21st century. Limiting global warming to 1.5°C during the course of the century may, therefore, open the window for many ecosystems to adapt or reassort geographically past climate change. This indicates a transition in risk in this system from high to very high (red to purple) (*high confidence*) at 1.5ºC warming and contributes to a lowering of the transition from high to very high (red to purple) in this RFC1 compared to AR5. Further details of risk transitions for ocean systems are described in Figure 3.20.

Substantial losses of Arctic Ocean summer ice were projected in AR5 WGI for global warming of 1.6ºC, with a nearly ice-free Arctic Ocean being projected for global warming of greater than 2.6ºC. Since AR5, the importance of a threshold between 1ºC and 2ºC has been further emphasized in the literature, with sea ice projected to persist throughout the year for a global warming less than 1.5ºC, yet chances of an ice-free Arctic during summer being high at 2°C warming (Section 3.3.8). Less of the permafrost in the Arctic is projected to thaw (21–37% under 1.5˚C warming as compared with 35–47% for 2˚C warming) (Section 3.3.5.2), which would be expected to reduce risks to both social and ecological systems in the Arctic. This indicates a transition in risk in this system from high to very high (red to purple) between 1.5ºC and 2˚C warming and contributes to a lowering of the transition from high to very high (red to purple) in this RFC1 compared to AR5.

AR5 identifies a large number of threatened systems including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems. These include the Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succuluent Karoo areas of S. Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, impacts accrue with greater warming and impacts at 2ºC being expected to be greater than those at 1.5ºC (*medium confidence*). One study since the AR5 has shown that constraining global warming to 1.5ºC would maintain the functioning of the prairie pothole ecosystem (north America) in terms of its productivity and biodiversity, whilst a warming of 2ºC would not do so (Carter Johnson et al., 2016). The large proportion of insects projected to lose over half their range at 2ºC warming (25%) as compared to 1.5°C warming (9%) also suggests a significant loss of functionality in these systems at 2ºC warming owing to the key role of insects in nutrient cycling, pollination, detritivory, and other key ecosystem processes (Section 3.4.2).

Unique and threatened systems in small island states and in systems fed by glacier meltwater were also considered in AR5 in making a contribution to this RFC, but there is little new information about these systems that pertains to 1.5ºor 2ºC global warming.

Taken together, the evidence suggests that the transition from high to very high risk (red to purple) in unique and threatened systems occurs at a lower level of warming, between 1.5ºC and 2ºC *(high confidence*), than in AR5 where this transition was located at 2.6ºC. The transition from moderate to high risk (yellow to red) would relocate very slightly from 1.6ºC to 1.5ºC.

3.5.2.2 *RFC 2- Extreme weather events*

In this sub-subsection reduced risks in terms of the likelihood of occurrence of extreme weather events are discussed for 1.5ºC as compared to 2ºC of global warming – for those extreme events where current evidence is available. AR5 assigned a moderate (yellow) level of risk due to extreme weather events at recent temperatures (1986-2005) due to the attribution of heat and precipitation extremes to climate change, and a transition to high (red) beginning below 1.6ºC global warming based on the magnitude, likelihood and timing of projected changes in risk associated with extreme events, indicating more severe and widespread impacts. The AR5 analysis already suggests a significant benefit of limiting warming to 1.5ºC, since this might keep risks closer to the moderate level. New literature since AR5 provides greater confidence in a reduced level of risks due to extreme weather events at 1.5ºC versus 2ºC for some types of extremes (see Section 3.3 and below).

Temperature: It is very likely that further increases in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes will occur under 1.5ºC of global warming compared to present-day climate (1°C warming), with further increases towards 2ºC of warming (section 3.3). As assessed in Sections 3.3.1 and 3.3.2, impacts of a 0.5°C global warming can be identified for temperature extremes at global scales, based on observations and the analysis of climate models. At 2ºC of global warming, it is likely that temperature increases of more than 2°C will occur over most land regions in terms of extreme temperatures (on average between 3 and 8°C depending on region and considered extreme index) (Section 3.3.2). Regional increases in temperature extremes under 1.5°C of global warming, can be reduced to 2–6°C (Section 3.3.2). Benefits to be obtained from this general reduction in extremes depends to a large extent on whether the lower range of increases in extremes at 1.5ºC is sufficient for critical thresholds to be exceeded, within the context of wide-ranging aspects such as crop yields, human health and the sustainability of ecosystems.

Heavy precipitation: AR5 assessed trends in heavy precipitation for land regions where observational coverage was sufficient for assessment. It concluded with medium confidence that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. A recent observations-based study also shows that a 0.5°C increase in global mean temperature has a detectable effect on changes in precipitation extremes at global scale (Schleussner et al., 2017), thus suggesting that there would be detectable differences in heavy precipitation at 1.5°C and 2°C of global warming. These results are consistent with analyses of climate projections, although they also highlight a large amount of regional variation in the sensitivity of changes in heavy precipitation (Section 3.3.3).

Droughts: When considering the difference between precipitation minus evaporation as a function of global temperature changes, the subtropics generally display an overall trend towards drying, whilst the northern high latitudes display a robust response towards increased wetting (Section 3.3.4, Figure 3.12). Limiting global mean temperature increase to 1.5°C as opposed to 2°C could substantially reduce the risk of reduced regional water availability (Section 3.3.4). Regions that are to benefit most include the Mediterranean region and southern Africa (Section 3.3.4). There are also some possible effects in parts of South America and on subregional scale in the Western Sahel (Section 3.3.4). Some possible effects are found in some other regions, mostly for the tails of multi-model projections (Fig. 3.12).

Fire: The increased amount of evidence that anthropogenic climate change has already caused significant increases in fire area globally (Section 3.4.3) is in line with projected fire risks. These risks are projected to increase further under 1.5ºC of global warming relative to the present day (Section 3.4.3). Under 1.2°C of global warming, fire frequency was estimated to increase by over 37.8% of global land areas, compared to 61.9% of global land areas under 3.5°C of warming. For in-depth discussion and uncertainty estimates, see (Meehl et al., 2007; Moritz et al., 2012; Romero-Lankao et al., 2014).

In "Extreme Weather Events" (RFC2) the transition from moderate to high risk is located between 1ºC and 1.5ºC global warming, which is very similar to the AR5 assessment but there is greater confidence in the assessment (*medium confidence*). The impact literature contains little information about the potential for human society to adapt to extreme weather events and hence it has not been possible to locate the transition from 'high' (red) to 'very high' risk within the context of assessing impacts at 1.5°C vs 2°C global warming.

There is thus *low confidence* in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report.

3.5.2.3 *RFC 3 - Distribution of impacts*

Risks due to climatic change are unevenly distributed and are generally greater at lower latitudes and for disadvantaged people and communities in countries at all levels of development. AR5 located the transition to moderate risk below recent temperatures owing to the detection and attribution of regionally differentiated changes in crop yields (*medium to high confidence*) and new literature continues to confirm this finding. Based on assessment of risks to regional crop production and water resources, AR5 located the transition from moderate to high risk between 1.6°C and 2.6°C above pre-industrial levels. Cross-Chapter Box 6 highlights that at 2°C warming, new literature shows that risks of food shortage are projected to emerge in the African Sahel, the Mediterranean, central Europe, the Amazon, western and southern Africa, and that these are much larger than the corresponding risks at 1.5°C. This suggests a transition from moderate to high risk of regionally differentiated impacts between 1.5°C and 2°C above pre-industrial levels for food security (medium confidence). Reduction in the availability of water resources for less than 2ºC is projected to be greater than 1.5ºC of global warming, although changes in socioeconomics could have a greater influence (Section 3.4.2), with larger risks in the Mediterranean (Box 3.2) but estimates of the magnitude of the risks remain similar to those cited in AR5. Globally, millions of people may be at risk from sea level rise during the 21st century (Hinkel et al., 2014; Hauer et al., 2016), particularly if adaptation is limited. At 2°C of warming, more than 70% of global coastlines will experience sea-level rise greater than 0.2 m, suggesting regional differences in the risks of coastal flooding. Regionally differentiated multi-sector risks are already apparent at 1.5°C warming, being more prevalent vulnerable people live, predominantly in South Asia (mostly Pakistan, India, and China), but these spread to sub-Saharan Africa, the Middle East and East Asia as temperature rises, with the world's poorest disproportionately impacted by 2°C (Byers et al., 2018). The hydrological impacts of climate change in Europe in a 1.5ºC, 2ºC and 3°C warmer world are intense and spatially more extensive (Donnelly et al., 2017). Taken together, a transition from moderate to high risk is now located between 1.5°C and 2°C above pre-industrial levels based on an assessment of risks to food security, water resources, drought, heat exposure and coastal submergence *(high confidence)*.

3.5.2.4 *RFC 4 - Global aggregate impacts*

Oppenheimer et al. (2014) explain the inclusion of non-economic metrics related to impacts on ecosystems and species at the global level, in addition to economic metrics in global aggregate impacts. The degradation of ecosystem services by climate change and ocean acifidification were in general excluded from previous global aggregate economic analyses.

Global economic impacts: WGII AR5 found that overall global aggregate impacts become moderate between 1–2ºC of warming and the transition to moderate risk levels was therefore located at 1.6ºC above pre-industrial levels. This was based on the assessment of literature using model simulations which indicate that the global aggregate economic impact will become significantly negative between 1ºC and 2ºC of warming (*medium confidence*), whilst there will be a further increase in the magnitude and likelihood of aggregate economic risks at 3ºC warming (*low confidence*).

Since AR5, three studies have emerged using two entirely different approaches which indicate that economic damages are projected to be higher by 2100 if warming reaches 2ºC than if it is constrained to 1.5ºC. The study of Warren et al. (2018c) uses the integrated assessment model PAGE09 to estimate that avoided global economic damages of 22% (10–26%) accrue from constraining warming to 1.5°C rather than 2°C, 90% (77–93%) from 1.5°C rather than 3.66°C, and 87% (74–91%) from 2°C rather than 3.66°C; while Petris et al. (2018) identify several regions in which economic damages are greater at 2°C warming compared to 1.5ºC, further estimating that projected damages at 1.5ºC remain similar to today's levels of economic damage. Another study (Burke et al., 2018) uses an empirical, statistical approach and finds that limiting warming to 1.5ºC instead of 2ºC would save 1.5–2.0% of Gross World Product (GWP) by mid-century and 3.5% of GWP by end-of-century (see figure 2A in Burke et al 2018), which under a 3% discount rate corresponds to $8.1-11.6 trillion and $38.5 trillion in avoided damages by mid- and end-of-century, respectively, agreeing closely with the Warren et al. (2018c) estimate of $15 trillion. In the no policy baseline temperature rises by 3.66°C by 2100, resulting in global GDP loss of 2.6% (5-95% percentile range 0.5–8.2%), as compared with 0.3% (0.1–0.5%) by 2100 in the 1.5°C scenario and 0.5% (0.1–1.0%) in the 2°C scenario. Limiting warming to 1.5°C rather than 2°C by 2060 has also been estimated to result in co-benefits of 0.5–0.6% of world GDP due to reductions in air pollution (Shindell et al., 2018) which is similar to the avoided damages identified for the USA (see below).

Two studies focusing only on the USA (Hsiang et al., 2017; Yohe, 2017) also found that economic damages are projected to be higher by 2100 if warming reaches 2ºC than if it is constrained to 1.5ºC (one study finds a mean difference 0.35% GDP, range 0.2–0.65%, the other identifies a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree). Further, the avoided risks compared to a 'no policy' baseline are greater in the 1.5ºC case (4%, range 2–7%) compared to the 2ºC case (3.5%, range 1.8–6.5%).

These analyses suggest that the point at which global aggregates of economic impacts become negative is below 2ºC (*medium confidence*), and that there is a possibility that this is below 1.5ºC warming.

Oppenheimer et al. (2014) note that the global aggregated damages associated with large scale singular events has not been explored, and reviews of integrated modelling exercises have indicated a potential underestimation of global aggregate damages due to the lack of consideration of the potential for these events in many studies. Since AR5, a further analysis of the potential economic consequences of triggering these large scale singular events (Y. Cai et al., 2016; Lemoine and Traeger, 2016), also indicates a two to eightfold larger economic impact associated with a warming of 3ºC than most previous analyses, depending on the number of events incorporated: Lemoine includes only three known singular events whereas (Y. Cai et al., 2016) include five.

Biome shifts, risks of species extinction and ecosystem functioning and services: 13% (range 8–20%) of the earth's land area is projected to undergo biome shifts under 2ºC warming compared to approximately 7% at 1.5°C warming (Section 3.4.3, Warszawski et al., 2013), hence implying a halving of biome transformations. Overall levels of species loss at 2ºC warming are similar to previous studies for plants and vertebrates (Warren et al., 2011; Warren et al., 2018b)but insects have been found to be more sensitive to climate change, with 18% (6–35%) projected to lose over half their range at 2ºC warming compared to 6% (1–18%) under 1.5°C warming, which is 66% (Section 3.4.3). The critical role of insects in ecosystem functioning therefore suggests impacts already on global ecosystem functioning at 2ºC warming. Since AR5 new literature indicates that impacts on marine fish stocks and fisheries are lower in 1.5–2°C global warming relative to pre-industrial level when compared to higher warming scenarios (Section 3.4.6) especially in tropical and polar systems.

In AR5, the transition from no impacts detected (white) to moderate impacts (yellow) was considered to occur between 1ºC and 2°C global warming, reflecting the impacts on the economy and on biodiversity globally; whereas high risks (red) were associated with 3°C warming to reflect the high risks to biodiversity and accelerated effects on the global economy. The new evidence suggests moderate impacts on the global aggregate economy and global biodiversity by 1.5°C, suggesting a lowering of the transition to moderate risk (yellow) already by 1.5°C; and higher risks than previously thought on the global aggregate economy and global biodiversity by 2°C global warming warming; suggesting that risks transition to high between 2°C and 3°C warming, as opposed to at 3°C as previously thought (*medium confidence)*.

3.5.2.5 *RFC 5 - Large scale singular events*

Large scale singular events are components of the global earth system that are thought to hold the risk of reaching critical tipping points under climate change, and that can result in or be associated with major shifts in the climate system. These components include:

- The cryosphere: West-Antarctic ice sheet, Greenland ice sheet
- The thermohaline circulation (slowdown of the Atlantic Meridional Overturning Current, AMOC).
- The El Niño-Southern Oscillation (ENSO) as a global mode of climate variability
- Role of the Southern Ocean in global carbon cycle

AR5 assessed that the risks associated with these events become moderate between 0.6ºC and 1.6°C above pre-industrial levels due to early warning signs and that risk becomes high between 1.6°C and 4.6°C due to the potential for commitment to large irreversible sea level rise from the melting of land based ice sheets (*low to medium confidence*). The increase in risk between 1.6ºC and 2.6°C above pre-industrial levels was assessed to be disproprortionately large. New findings since AR5 are detailed below.

Greenland and West-Antarctic ice sheets and Marine Ice Sheet Instability: Various feedbacks between the Greenland ice sheet and the wider climate system (most notably those related to the dependence of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a possibility. Church et al. (2013) assess this threshold to be 2°C or higher (relative to pre-industrial temperature).

Robinson et al. (2012) find a range for this threshold of 0.8–3.2°C (95% confidence). The threshold of global temperature increase that may initiate irreversible loss of the West-Antarctic ice sheet and Marine Ice Sheet Instability (MISI) is estimated to range between 1.5ºC and 2°C. The timescale for eventual loss of the ice sheets varies between millennia and tens of millennia and assumes constant surface temperature forcing during this period. Were temperature to cool subsequently, the ice sheets might regrow although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat. The magnitude of global sea level rise plausible to occur over the next two centuries under 1.5–2°C of global warming is estimated to be in the order of several tenths of a meter by most studies (*low confidence*) (Schewe et al., 2011; Church et al., 2013; Levermann et al., 2014; Marzeion and Levermann, 2014; Fuerst et al., 2015; Golledge et al., 2015), although a smaller number of investigations (Joughin et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016) project increases of 1–2 m. This body of evidence suggest that the temperature range of 1.5–2ºC may be regarded as representing moderate risk (it may trigger MISI in Antarctica or irreversible loss of the Greenland ice sheet and it may be associated with sea-level rise as high as 1–2 m over a period of two centuries).

Thermohaline circulation (slowdown of AMOC): It is more likely than not that the AMOC has been weakening in recent decades, given the detection of the cooling of surface waters in the North Atlantic and evidence that the Gulf Stream has slowed by 30% since the late 1950s (Srokosz and Bryden, 2015; Caesar et al., 2018). There is limited evidence linking the recent weakening of the AMOC to anthropogenic warming (Caesar et al., 2018). It is very likely that the AMOC will weaken over the 21st century. Best estimates and range for the reduction from CMIP5 are 11% (1–24%) in RCP2.6 and 34% (12–54%) in RCP8.5 (AR5). There is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5°C vs 2°C of global warming, or of a shutdown of the AMOC at these global temperature thresholds. Associated risks are classified as low to medium.

El Niño-Southern Oscillation (ENSO)*:* Extreme El Niño events are associated with significant warming of the usually cold eastern Pacific Ocean, and occur about once every 20 years (Cai et al., 2015). Such events reorganize the distribution of regions of organized convection, and affect weather patterns across the globe. Recent research (G. Wang et al., 2017) indicate that the frequency of extreme El Niño events increases linearly with the global mean temperature, and that the number of such events might double (one event every ten years) under 1.5°C of global warming. This pattern is projected to persist for a century after stabilization at 1.5°C, thereby challenging the limits to adaptation, and thus indicating high risk even at the 1.5°C threshold. La Niña event frequencies are projected to remain similar to that of the present-day under 1.5–2°C of global warming.

Role of the Southern Ocean in the global carbon cycle*:* The critical role of the Southern Ocean as a net sink of carbon might decline under global warming, and assessing this effect under 1.5ºC compared to 2ºC of global warming is a priority. Changes in ocean chemistry (e.g., oxygen content, ocean acidification), especially those associated with the deep sea, are associated concerns (Section 3.3.10).

Large scale singular events (RFC5) moderate risk is now located at 1ºC and high risks are located 2ºC, as opposed to 1.9ºC (moderate) and 4ºC (high) risk in AR5 because of new observations and models of the West Antarctic ice sheet (medium confidence), which suggests the ice sheet may be in the early stages of Marine Ice Sheet Instability (MISI). Very-high risk is assessed as lying above 5ºC because the growing literature on process-based projections of the West Antarctic ice sheet predominantly supports the AR5 assessment of a MISI contribution of an additional several tenths of a metre by 2100.

3.5.3 Regional economic benefit analysis for the 1.5°C vs 2°C global temperature goals

This section reviews recent literature that estimates the economic benefits for constraining global warming to 1.5°C as compared to 2°C. The focus here is on evidence pertaining to specific regions, rather than on global aggregated benefits (Section 3.5.2.4). At 2°C of global warming, lower economic growth is projected for many countries, with low-income countries projected to experience the greatest losses (*limited evidence, medium confidence*) (Burke et al., 2018; Petris et al., 2018). A critical issue for developing countries in particular is that advantages in some sectors are projected to be offset by the increasing mitigation costs (Rogelj et al., 2013; Burke et al., 2018)– with food production being a key factor. That is, although restraining the global temperature increase to 2°C is projected to reduce crop losses under climate change, relative to higher levels of warming, the associated mitigation costs may increase the risk of hunger in low-income countries (*low confidence*) (Hasegawa et al., 2016). It is *likely* that the even more stringent mitigation measures required to restrict global warming to 1.5°C (Rogelj et al., 2013) will further increase these mitigation costs and impacts. International trade in food might be a key response measure for alleviating hunger in developing countries under 1.5°C and 2°C stabilization scenarios (Hasegawa et al., 2016).

Although warming is projected to be the highest in the Northern Hemisphere under 1.5ºC or 2°C of global warming, regions in the tropics and Southern Hemisphere subtropics that are projected to experience the largest impacts on economic growth (*limited evidence, medium confidence*) (Gallup et al., 1999; Burke et al., 2018; Petris et al., 2018). Despite the uncertainties associated with climate change projections and econometrics (e.g., Burke et al., 2016), it is *more likely than not* that there will be large differences in economic growth under 1.5°C and 2°C of global warming for developing versus developed countries (Burke et al., 2018; Petris et al., 2018). Statistically significant reductions in Gross Domestic Product (GDP) per capita growth are projected across much of the African continent, southeast Asia, India, Brazil and Mexico (*limited evidence, medium confidence*). Countries in the western parts of tropical Africa are projected to benefit most from restricting global warming to 1.5°C as opposed to 2°C, in terms of future economic growth (Petris et al., 2018). An important reason why developed countries in the tropics and subtropicas are to benefit substantially from restricting global warming to 1.5°C, relates to present-day temperatures in these regions being above the threshold thought to be optimal for econonomic production (Burke et al., 2015b, 2018).

The world's largest economies are also projected to benefit from restricting warming to 1.5°C, as opposed to 2°C (*medium confidence*), with the likelihood of such benefits to be realized estimated to be 76%, 85% and 81% for the USA, China and Japan, respectively (Burke et al., 2018). Two studies focusing only on the USA (Hsiang et al., 2017; Yohe, 2017) also found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5ºC (one study finds a mean difference 0.35% GDP, range 0.2–0.65%, the other identifies a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree). Indeed, no statistically significant changes in GDP are projected to occur over most of the developed world (*limited evidence, low confidence*) (Petris et al., 2018).

A caveat of the analysis of Petris et al. (2018) and Burke et al. (2018) is that the effects of sea-level rise are not included in the estimations of damages or future economic growth, implying a potentiall underestimate of the benefits of limiting warming to 1.5°C, for the case where significant sea level rise is avoided at 1.5°C but exceeded at 2°C.

3.5.4 Reducing hot spots of change for 1.5°C and 2°C global warming

This sub-section integrates Sections 3.3 and 3.4 in terms of climate change induced hot-spots that occur through interactions across the physical climate system, ecosystems and socio-economic human systems, with a focus on the extent to which risks can be avoided or reduced by achieving the 1.5°C global temperature goal (as opposed to the 2°C goal). Findings are summarised in Table 3.6.

3.5.4.1 Arctic sea ice

Ice-free Arctic Ocean summers are *very likely* at levels of global warming higher than 2°C (Notz and Stroeve, 2016; Rosenblum and Eisenman, 2016; Screen and Williamson, 2017; Niederdrenk and Notz, 2018). Some studies are even indicative of the entire Arctic Ocean summer period becoming ice-free under 2°C of global warming whilst other more conservatively estimate this probability to be in the order of 50% (Sanderson et al., 2017; Section 3.3.8). The probability for an ice-free Arctic in September at 1.5°C of global warming is low and substantially lower than for the case of 2°C of global warming *(high confidence)* (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Section 3.3.8). There is, however, a single study that questions the validity of the 1.5°C threshold in terms of maintaining summer Arctic Ocean sea-ice (Niederdrenk and Notz, 2018). Finally, during winter, only little ice is projected to be lost for either 1.5°C or 2°C global warming (*medium confidence*) (Niederdrenk and Notz, 2018). The losses in sea ice at 1.5ºC and 2°C of warming will result in habitat losses for organisms such as seals, polar bears, whales and sea-birds (e.g., Larsen et al., 2014). There is *high agreement* and *robust evidence* that photosynthetic species will change due to sea-ice retreat and related changes in temperature and radiation (Section 3.4.4.7), and this is *very likely* to benefit fisheries productivity in the Northern Hemisphere spring bloom system (Section 3.4.4.7).

3.5.4.2 Arctic land regions

In some Actic land regions, the warming of cold extremes and annual minimum temperature at 1.5°C is stronger than the global mean temperature increase by a factor of 2–3, i.e. 3°C -4.5°C regional warming at 1.5°C global warming (e.g., northern Europe, Annex 3.1 Figure S3.6 – also see Section 3.3.2.2 and Seneviratne et al., 2016). Moreover, over much of the Arctic, a further increase of 0.5°C in the global surface temperature, from 1.5 to 2°C may lead to further temperature increases of 2–2.5°C (Figure 3.3). As a consequence, biome (major ecosystem types) shifts are *likely* in the Arctic, with increases in fire frequencies, degradation in permafrost and increases in tree cover *likely* to occur under at 1.5ºC warming, with further amplification of these changes under 2ºC of global warming (e.g., Gerten et al., 2013; Bring et al., 2016). Rising temperatures, thawing permafrost and changing weather patterns will increasingly impact on people, infrastructure and industries in the Arctic (W.N. Meier et al., 2014), with these impacts larger at 2°C vs 1.5°C of warming (*medium confidence*).

3.5.4.3 Alpine regions

Alpine regions are generally regarded as climate change hotspots given their generally cold and harsh climates in which a rich biodiversity has evolved, but which are vulnerable to increases in temperature. Under regional warming, alpine species have been found to migrate upwards on mountain slopes (Reasoner and Tinner, 2009), an adaptation response with obvious limited by mountain height and habitability. Moroever, many of the world's Alpine regions are important from a water security perspective through associated glacier melt, snow melt and river flow (Section 3.3.5.2 for a discussion of these aspects). Projected biome shifts are already *likely* to be severe in alpine regions at 1.5ºC warming and increase further for 2ºC warming (Chen et al., 2014a; Gerten et al., 2013; Figure 1b).

3.5.4.4 Southeast Asia

Southeast Asia is a region highly vulnerable to increased flooding in the context of sea-level rise (Arnell et al., 2016; Brown et al., 2016, 2018a). Risks from increased flooding rise from 1.5°C to 2°C of warming (*medium confidence*), with substantial increases beyond 2°C (Arnell et al., 2016). Southeast Asia displays statistically significant differences in projected changes in heavy precipitation, run-off and high flows at 1.5°C versus 2°C warming (with stronger increase at 2°C; (Wartenburger et al., 2017; Döll et al., 2018; Seneviratne et al., 2018a); Section 3.3.3), and thus is thought to be a hotspot in terms of increases in heavy precipitation between these two global temperature levels (Schleussner et al., 2016b; Seneviratne et al., 2016) (*medium confidence*). For Southeast Asia, a 2°C warming by 2040 indicated a one-third decline in per capita crop production (Nelson et al., 2010) associated with general decreases in crop yields. However, under

1.5°C of warming, significant risks for crop yield reduction in the region are avoided (Schleussner et al., 2016b). These changes pose significant risks for poor people in both rural regions and urban areas of Southeast Asia (Section 3.4.10.1), with these risks being larger at 2°C of global warming compared to 1.5°C of warming (*medium confidence*).

3.5.4.5 Southern Europe and the Mediterranean

The Mediterranean is regarded as a climate change hot spot both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature warming (e.g., Seneviratne et al., 2016) and projected substantial decreases in mean precipitation with associated substantial increases in dry spells. The latter is projected to increase from 7% to 11% when comparing regional impacts at 1.5°C versus 2°C of global warming, respectively (Schleussner et al., 2016b). Low river flows are projected to decrease in the Mediterranean under 1.5°C of global warming (Marx et al., 2018) with associated significant decreases in high flows and floods (Thober et al., 2018), largely in response to reduced precipitation. The median reduction in annual runoff almost double from about 9% (likely range: 4.5–15.5%) at 1.5°C to 17% (likely range: 8–25%) at 2°C (Schleussner et al., 2016b). Similar results are found by (Döll et al., 2018). Overall, there is *high confidence* of strong increases in dryness and decreases in water availability in the Mediterranean and southern Europe from 1.5ºC to 2°C of global warming. Sea-level rise is expected to be lower for 1.5ºC versus 2°C, lowering risks for coastal metropolitan agglomerations. The risks (with current adaptation) related to water deficit in the Mediterranean are high for a global warming of 2°C, but can be substantially reduced if global warming is limited to 1.5°C (Guiot and Cramer, 2016; Schleussner et al., 2016b; Donnelly et al., 2017; Section 3.3.4).

3.5.4.6 West Africa and the Sahel

West Africa and the Sahel are *likely* to experience increases in the number of hot nights and longer and more frequent heat waves even if the global temperature increase is constrained to 1.5°C, with further increase at 2°C of global warming and beyond (e.g., Weber et al., 2018). Moreover, the daily rainfall intensity and run-off is expected to increase (*low confidence*) towards 2°C and higher global warming scenarios (Weber et al., 2018; Schleussner et al., 2016b), with these changes also being relatively large compared to the projected changes at 1.5°C of warming. Moreover, increased risks are projected in terms of drought, particularly for the pre-monsoon season (Sylla et al., 2015), with both rural and urban populations affected, and increasingly so at 2°C of global warming as opposed to 1.5°C (Liu et al., 2018). Based on a World Bank (2013) study for sub-Saharan Africa, a 1.5°C warming by 2030 might reduce the present maize cropping areas by 40%, rendering these no longer suitable for current cultivars. Substantial negative impacts are also projected for sorghum suitability in the western Sahel (Läderach et al., 2013; Sultan and Gaetani, 2016). Increase in warming (2°C) by 2040 would result in further yield losses and damages to crops (i.e., maize, sorghum, wheat, millet, groundnut, cassava). Schleussner et al. (2016b) consistently indicate reduced impacts on crop yield for West Africa under 2°C vs 1.5°C of global warming. There *is medium confidence* that vulnerabilities to water and food security in the African Sahel will be higher at 2°C compared to 1.5°C of global warming (Cheung et al., 2016b; Betts et al., 2018), and at 2°C these vulnerabilities are expected to be worse (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high evidence).* For global warming greater than 2°C, the western Sahel might experience the strongest drying and experience serious food security issues (Ahmed et al., 2015; Parkes et al., 2018).

3.5.4.7 *Southern Africa*

The southern African region is projected to be a climate change hot spot in terms of both hot extremes (Figures 3.5 and 3.6) and drying (Figure 3.12). Indeed, temperatures have been rising in the subtropical regions of southern Africa at approximately twice the global rate over the last five decades (Engelbrecht et al., 2015). Associated elevated warming of the regional land-based hot extremes has occurred (Section 3.3; Seneviratne et al., 2016). Increases in the numer of hot nights as well as longer and more frequent heat waves are projected even if the global temperature increase is constrained to 1.5°C *(high confidence)*, with further increase at 2°C of global warming and beyond *(high confidence)* (Weber et al., 2018).

Moreover, the region is *likely* to become generally drier with reduced water availability under low mitigation (Niang et al., 2014; Engelbrecht et al., 2015; Karl et al., 2015; James et al., 2017), with this particular risk also prominent under 2°C of global warming and even 1.5ºC of warming (Gerten et al., 2013). Risks are significantly reduced, however, under 1.5°C of global warming (Schleussner et al., 2016b). There are consistent and statistically significant projected increases in risks of increased meteorological drought in southern Africa at 2°C vs 1.5°C of warming (*medium confidence*). Despite the general rainfall reductions projected for southern Africa, daily rainfall intensities are expected to increase over much of the region (*medium confidence)*, and increasingly so with further amounts of global warming. There is medium confidence that livestock in southern Africa will experience increased water stress under both 1.5ºC and 2°C of global warming, with negative economic consequences (e.g., Boone et al., 2017). The region is also projected to experience reduced maize, sorghum and cocoa cropping area suitability as well as yield losses under 1.5°C of warming, with further decreases towards 2°C of warming (World Bank, 2013). Generally, there is *high confidence* that vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C for southern Africa (Betts et al., 2018), whilst at 2°C these are expected to be higher (Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high confidence*).

3.5.4.8 *Tropics*

Worldwide, the largest increases in the number of hot days are projected to occur in the tropics (Figure 3.7). Moreover, the largest differences in the number of hot days for 1.5°C of global warming versus 2°C of global warming are found in the tropics (Mahlstein et al., 2011). In tropical Africa, increases in the number of hot nights, as well as longer and more frequent heat waves, are projected under 1.5°C of global warming, with further increases under 2°C of global warming (Weber et al., 2018). Impact studies for major tropical cereals reveal that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Schleussner et al. (2016b) project that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and Central and South America. There is *limited evidence* and thus *low confidence* that these changes may result in significant population displacement from the tropics to the subtropics (e.g., Hsiang and Sobel, 2016).

3.5.4.9 *Small islands*

Small islands are well recognized to be very sensitive to climate change impact such as sea-level rise, oceanic warming, precipitation, cyclones and coral bleaching (high agreement, robust evidence) (Nurse et al., 2014; Ourbak and Magnan, 2017). Even at 1.5°C of global warming, the compounding impacts of changes in rainfall, temperature, tropical cyclones and sea levels are likely to be significant across multiple natural and human systems. There are potential benefits to Small Island Developing States (SIDS) from avoided risks at 1.5˚C versus 2˚C, especially when coupled with adaptation efforts. In terms of sea-level rise, by 2150, roughly 40,000 less people living in SIDS will be inundated in a 1.5°C world than in a 2˚C world

(Rasmussen et al., 2018). Constraining global warming to 1.5ºC would significantly reduce water stress (about 25%) as compared to the projected water stress at 2ºC (e.g., Caribbean region, Karnauskas et al., 2018), and may enhance the ability of SIDS to adapt (Benjamin and Thomas, 2016). Up to 50% of the year is projected to be very warm in the Caribbean for 1.5°C, with a further increase by up to 70 days for 2˚C versus 1.5˚C (Taylor et al., 2018). By limiting warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding (measured as the flood amplification factors for 100-year flood events) are reduced between 20 and 80% for SIDS (Rasmussen et al., 2018). A case study of Jamaica with lessons for other Caribbean SIDS demonstrates that the difference between 1.5ºC and 2°C is likely to challenge livestock thermoregulation, resulting in persistent heat stress for livestock (Lallo et al., 2018).

3.5.4.10 Fynbos and shrub biomes

The Fynbos and succulent Karoo biomes of South Africa are threatened systems that have been assessed in AR5. Similar shrublands exists in the semi-arid regions of other continents, the Sonora-Mojave Creosotebush-White Bursage Desert Scrub ecosystem in the USA being a prime example. Impacts accrue across these systems with greater warming, with impacts at 2°C likely to be greater than those at 1.5°C (*medium confidence*). Under 2°C of global warming, regional warming in drylands will be 3.2–4°C and under 1.5°C of global warming, mean warming in drylands will still be about 3°C. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters (*high confidence*). The Fynbos biome is projected to lose about 20%, 45% and 80% of its current suitable climate area under 1°C, 2°C and 3°C of warming with respect to present-day climate (Engelbrecht and Engelbrecht, 2016), demonstrating the value of climate change mitigation in protecting this rich centre of biodiversity.

Table 3.6: Emergence and intensity of climate change hot-spots under different degrees of global warming

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C
Arctic sea-ice	Arctic summer sea-ice is *likely* to be maintained. Habitat losses for organisms such as polar bears, whales, seals and sea-birds Benefits for arctic fisheries	The risk of an ice free Arctic in summer is ~ 50% or higher. Habitat losses for organisms such as polar bears, whales, seals and sea-birds may be critical if summers are ice-free Benefits for arctic fisheries	Arctic is *very likely* to be ice-free in summer. Critical habitat losses for organsims such as polar bears, whales, seals and sea-birds Benefits for arctic fisheries
Arctic land regions	Cold extremes warm by a factor of 2.5-3, reaching up to 5.5 °C *(high confidence)* Biome shifts in the tundra and	Cold extremes warm by as much as 8 °C *(high confidence)* Larger intrusions of trees and shrubs in the tundra than under 1.5 °C of warming	Drastic regional warming is *very likely* A collapse in permafrost may

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C
	permafrost deterioration is *likely*	is *likely*; larger but constrained losses in permafrost are *likely*	plausibly occur (*low confidence*); a drastic biome shift from tundra to boreal forest is possible *(low confidence*).
Alpine regions	Severe shifts in biomes are *likely* Reduced grassland net primary productivity	Even more severe shifts are *likely* Increased risks for reduced grassland net primary productivity	Critical losses in alpine habitats are *likely* Increased risks for significantly reduced grassland net primary productivity
Southeast Asia	Risks for increased flooding related to sea-level rise Increases in heavy precipitation events Significant risks of crop yield reductions are avoided	Higher risks for increased flooding related to sea-level rise *(medium confidence)* Stronger increases in heavy precipitation events *(medium confidence)* One third decline in per capita crop production *(medium confidence)*	Substantial increases in risks related to flooding from sea-level rise Substantial increased in heavy precipitation and high flow events Substantial reductions in crop yield
Small Islands	Land of 40,000 less people inundated by 2150 on SIDS Risks for coastal flooding reduced by 20-80% for SIDS Fresh water stress reduced by 25% Increase in the	Tens of thousands displaced due to inundation of SIDS High risks for coastal flooding Fresh water stress from projected aridity Further increase of about 70 warm days per year	Substantial and wide-spread impacts through indundation of SIDS, coastal flooding, fresh water stress, persistent heat stress and loss of most coral reefs very likely

Region and/or Phenomena	**Warming of 1.5ºC or less**	**Warming of 1.5ºC-2°C**	**Warming of 2°C - 3°C**
	number of warm days for SIDS in the tropics Persistent heat stress in cattle avoided Loss of 70-90% of coral reefs	Persistent heat stress in cattle in SIDS Loss of most coral reefs – remaining structures weaker due to ocean acidification	
Mediterranean	Increase (about 7%) in dry-spells Reduction in runoff of about 9% (likely range: 4.5–15.5%) Risk of water deficit	*High confidence* of further increases (11%) in dry spells *High confidence* of further reductions (about 17%) in runoff (likely range 8–28%) Higher risks for water deficit	Substantial reductions in precipitation and reductions in runoff *very likely* Very high risks for water deficit
West African and the Sahel	Reduced maize and sorghum production is *likely,* with suitable for maize production reduced by as much as 40% Increased risks for under-nutrition	Negative impacts on maize and sorghum production *likely* larger than at 1.5 °C Higher risks for undernutrition;	Negative impacts on crop yield may result in major regional food insecurities (*medium confidence*) High risks for undernutrition
Southern African savannahs and drought	*Likely* reductions in water availability High risks for increased mortality from heat-waves; High risk for undernutrition in communities dependent on dryland agriculture and livestock	Even larger reductions in rainfall and water availability *likely*; Higher risks for increased mortality from heat-waves (*high confidence*); Higher risks for undernutrition in communities dependent on dryland agriculture and livestock	Large reductions in rainfall and water availability are *likely* Very high risks for undernutrition in communities dependent on dryland agriculture and livestock

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C
Tropics	Accumulated heat-wave duration up to two months *(high confidence)*; 3% reduction in maize crop yield.	Accumulated heat-wave duration up to three months *(high confidence)*; 7% reduction in maize crop yield.	Oppressive temperatures and accumulated heat-wave duration *very likely* to directly impact on human health, mortality and productivity Substantial reductions in crop yield *very likely*
Fynbos biome	About 30% of suitable climate area lost *(medium confidence)*	Increased losses (about 45%) of suitable climate area *(medium confidence)*	Up to 80%of suitable climate area lost*(medium confidence)*

3.5.5 Avoiding regional tipping points by achieving more ambitious global temperature goals

Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as ecosystems and human systems, is essential for understanding the risks and opportunities from mitigation. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems is also analysed. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5ºC and 2ºC of global warming – note that tipping points in the global climate system, referred to as large scale singular events, have already been discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7.

3.5.5.1 Arctic sea-ice

Collins et al. (2013) discuss the loss of Artic sea ice in the context of potential tipping points. Climate models have been used to assess whether a bifurcation exists that would lead to the irreversible loss of Arctic sea ice (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) and to test whether summer sea ice extent can recover after it has been lost (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011). These studies do not find evidence of bifurcation and find that sea ice returns within a few years of its loss, leading Collins et al. (2013) to conclude that there is little evidence for a tipping point in the transition from perennial to seasonal ice cover. Studies do not find evidence of irreversibility or tipping points, and suggest that year-round sea ice could return with years given a suitable climate (*medium confidence*) (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011).

3.5.5.2 *Tundra*

Tree-growth in tundra-dominated landscapes is strongly constrained by the number of days above 0°C. A potential tipping points exists, where the number of days below 0°C decrease to the extent that tree fraction increases significantly. Tundra-dominated landscapes have warmed more than the global average over the last century (Settele et al., 2014), with associated increases in fires and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). Both of these processes facilitate conditions for woody species establishment in tundra areas, and the eventual transition of the tundra to boreal forest. The number of investigations into how the tree-fraction may respond in the Arctic to different degrees of global warming is limited, and generally indicative that substantial increases will likely occur gradually (e.g., Lenton et al., 2008). Abrupt changes only plausible at levels of warming significantly larger than 2°C (*low confidence*) and are to occur in conjunction with a collapse in permafrost (Drijfhout et al., 2015).

3.5.5.3 *Permafrost*

Widespread thawing of permafrost potentially makes a large carbon store (estimated to be twice the size of the atmospheric store, Dolman et al., 2010) vulnerable to decomposition, which would lead to further increases in atmospheric carbon dioxide and methane and hence further global warming. This feedback loop between warming and the release of greenhouse gas from thawing tundra represents a potential tipping point. However, the carbon released from thawing permafrost is projected to be restricted to 0.12-0.25 Gt C a^{-1} to the atmosphere in a 2ºC world, and to 0.08-0.16 Gt C $a^{-1}$for 1.5ºC (Burke et al., 2006), and thus do not represent a tipping point *(medium confidence*). At higher degrees of global warming, in the order of 3°C, a different type of tipping point in permafrost may be reached. A single model projection (Drijfhout et al., 2015) suggests that higher temperatures may induce a smaller ice fraction in soils in the tundra, leading to more rapidly warming soils and a positive feedback mechanism that results in permafrost collapse (*low confidence*). The disparity between the multi-millennial timescales of soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of this carbon to the atmosphere is essentially irreversible (Collins et al., 2013).

3.5.5.4 *Asian monsoon*

It is the pressure gradient between the Indian Ocean and Asian continent that at a fundamental level determines the strength of the Asian monsoon. As land masses warm faster than the oceans, a general strengthening of this gradient, and hence monsoons, may be expected under global warming (e.g., Lenton et al., 2008). Additional factors such as changes in albedo induced by aerosols and snow-cover change may also affect temperature gradients and consequently pressure gradients and the strength of the monsoon. In fact, it has been estimated that an increase of the landmass albedo to 0.5 would represent a tipping point resulting in the collapse of the monsoon system (Lenton et al., 2008). The overall impacts of the various types of radiative forcing under different emission scenarions are more subtle, with a weakening of the monsoon north of about 25°N in East Asia and a strengthening south of this latitude projected by (Jiang and Tian, 2013) under high and modest emission scenarios. Increases in the intensity of monsoon precipitation is likely under low mitigation (AR5). Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian (2013) there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding the differences between responses at 1.5°C versus 2°C levels of global warming.

3.5.5.5 *West African monsoon and the Sahel*

Earlier work has identified 3°C of global warming as a tipping point leading to a significant strengthening of the West African monsoon and subsequent wettening (and greening) of the Sahel and Saharah (Lenton et al., 2008). AR5 (Niang et al., 2014) as well as more recent research through the Coordinated Regional Downscaling Experiment for Africa (CORDEX-AFRICA) provide a more uncertain view, however, in terms of the rainfall futures of the Sahel under low mitigation futures. Even if a wetter Sahel should materialize under 3°C of global warming (*low confidence)*, it should be noted that there will be significant offsets in the form of strong regional warming and related adverse impacts on crop yield, livestock mortality and human health under such low mitigation futures (Engelbrecht et al., 2015; Sylla et al., 2016; Weber et al., 2018b)

3.5.5.6 *Rain forests*

A large portion of rainfall over the world's largest rainforests are recirculated (e.g., Lenton et al., 2008), which raises the concern that deforestation may trigger a threshold in reduced forest cover leading to pronounced forest dieback. For the Amazon, this deforestation threshold has been estimated to be 40% (Nobre et al., 2016). Global warming of 3°C–4°C may also, independent of deforestation, represent a tipping point that results in a significant dieback of the Amazon forest, with a key forcing mechanism being stronger El Niño envents bringing more frequent droughts to the region (Nobre et al., 2016). Increased fire frequencies under global warming may interact with and accelerate deforestation, particularly during periods of El Niño induced droughts (Lenton et al., 2008; Nobre et al., 2016). Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass productivity being reduced by more than 50%, and a large replacement of rainforest by savanna and grassland (Lyra et al., 2017). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) suggest that pronounced rainforest dieback may only be triggered at 3°C–4 °C (*medium confidence*), although pronounced biomass losses may occur at 1.5°C and 2°C of global warming.

3.5.5.7 *Boreal forests*

Boreal forests are likely to experience higher local warming than the global average (WGII AR5: Collins et al., 2013). Increased disturbance from fire, pests and heat related mortality may affect in particular the southern boundary of boreal forests (Gauthier et al., 2015) (*medium confidence*), with these impacts accruing with greater warming and thus impacts at 2°C would be expected to be greater than those at 1.5°C (*medium confidence*). A tipping point for significant dieback of the boreal forests is thought to exist, where increased tree mortality will result in the creation of large regions of open woodlands and grasslands, which would favour further regional warming and increased fire frequencies, thus inducing a powerful positive feedback mechanism (Lenton et al., 2008; Lenton, 2012). This tipping point has been estimated to exist between 3 and 4°C of global warming (Lucht et al., 2006; Kriegler et al., 2009) (*low confidence*), but given the complexities of the various forcing mechanisms and feedback processes this is thought to be an uncertain estimate.

3.5.5.8 *Heat-waves, unprecedented heat and human health*

Increases in ambient temperature are linearly related with hospitalizations and deaths (so there isn't a tipping point per se) once specific thresholds are exceeded. It is plausible that coping strategies will not be in place for many regions, with potentially significant impacts on communities with low adaptive capacity, effectively representing the occurrence of a local/regional tipping point. In fact, even if global warming is restricted to below 2°C, taking into consideration urban heat island effects, there could be a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, but substantially larger than under the present climate (Matthews et al., 2017). At +1.5°C, twice as many megacities as present (such as Lagos, Nigeria, and Shanghai, China) are *likely* to become heat stressed, potentially exposing more than 350 million more people to deadly heat stress by 2050. At +2°C warming, Karachi (Pakistan) and Kolkata (India) could expect annual conditions equivalent to their deadly 2015 heatwaves (*medium confidence*). These statistics imply a tipping point in the extent and scale of heat-wave impacts. However, these projections do not integrate adaptation to projected warming, for instance, cooling that could be achieved with more reflective roofs and urban surfaces overall (Akbari et al., 2009; Oleson et al., 2010).

3.5.5.9 Agricultural systems: key staple crops

A large number of studies consistently indicate that maize crop yield will be negatively affected under increased global warming, with negative impacts being higher under 2°C of warming than at 1.5°C of warming (e.g., Niang et al., 2014; Schleussner et al., 2016b; J. Huang et al., 2017; Iizumi et al., 2017). Under 2°C of global warming, losses of 8-14% are projected in global maize production (Bassu et al., 2014). Under more than 2°C of global warming, regional losses are projected to be about 20% if they co-occur with reductions in rainfall (Lana et al., 2017). These changes may be classified as incremental rather than representing a tipping point. Large-scale reductions in maize crop yield including the potential for the collapse of this crop in some regions may exist under 3°C or more of global warming (*low confidence*) (e.g., Thornton et al., 2011).

3.5.5.10 Agricultural systems: livestock in the tropics and subtropics

The potential impacts of climate change on livestock (Section 3.4.6) and in particular direct impacts through inceased heat-stress has been less well studied than impacts on crop yield, in particular from the perspective of critical thresholds being exceeded. A case study of Jamaica reveals that the difference in heat stress for livestock between 1.5°C and 2°C is likely to exceed the limits for normal thermoregulation and result in persistent heat stress for livestock animals (Lallo et al., 2018). It is plausible that this finding holds for livestock production in both tropical and subtropical regions more generally (*medium confidence*) (see Section 3.4.6). It is plausible that under 3°C of global warming, significant reductions in the areas suitable for livestock production occur (*low confidence*) due to strong increases in regional temperatures in the tropics and subtropics (*high confidence).* Thus, regional tipping points in the viability of livestock production may well exist, but little evidence quantifying such changes exist.

Table 3.7: Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals.

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
Arctic sea-ice	Arctic summer sea-ice is *likely* to be maintained. Sea-ice changes reversible under suitable climate restoration	The risk of an ice free Arctic in summer is ~ 50% or higher. Sea-ice changes reversible under suitable climate restoration	Arctic is *very likely* to be ice-free in summer. Sea-ice changes reversible under suitable climate restoration
Tundra	Decrease in number of growing degree days	Further decreases in number of growing	Potential for an abrupt increase in tree-

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
	below 0°C Abrupt increases in tree-cover are *unlikely*	degree days below 0°C Abrupt increased in tree cover are unlikely	fraction (*low confidence*)
Permafrost	21-37% reduction in permafrost 2 million km^2 more permafrost maintained than under 2°C of global warming (*medium confidence*) 0.08-0.16 Gt C a^{-1} released Irreversible loss of stored carbon	35-47% reduction in permafrost 0.12-0.25 Gt C a^{-1} released Irreversible loss of stored carbon	Potential for permafrost collapse (*low confidence*)
Asian Monsoon	*Low confidence* in projected changes	*Low confidence* in projected changes	Increases in the intensity of monsoon precipitation *likely*.
West African monsoon and the Sahel	Uncertain changes, *unlikely* that a tipping point is reached	Uncertain changes, *unlikely* that tipping point is reached	Strengthening of monsoon and wettening and greening of Sahel and Saharah *(low confidence)* Negative associated impacts through increase in extreme temperature events
Rainforests	Reduced biomass, deforestation and fire increases pose uncertain risks to forest dieback	Larger biomass reductions than under 1.5 °C warming, deforestation and fire increases pose uncertain risk to forest dieback	Potential tipping point leading to pronounced forest dieback *(medium confidence)*
Boreal forests	Increased tree mortality at southern boundary of boreal forest *(medium confidence*)	Further increases in tree mortality at southern boundary of boreal forest (*medium confidence)*	Potential tipping point for significant dieback of boreal forest (*low confidence*)
Heat-waves, unprecedented heat	Substantial increase in occurrence of potentially	Substantial increase in potentially deadly	Substantial increase in potentially deadly

Tipping point	**Warming of 1.5ºC or less**	**Warming of 1.5ºC-2°C**	**Warming of up to 3°C**
and human health	deadly heat-waves *likely* More than 350 million more people exposed to deadly heat by 2050 under a midrange population growth scenario	heat-waves *likely* Annual occurrence of heat-waves similar to deadly 2015 heat-waves in India and Pakistan	heat-waves *very likely*
Key staple crops	Global maize crop reductions of about 10%	Larger reductions in maize crop production that under 1.5°C of about 15%	Drastic reductions in maize crop globally and in Africa *(high confidence),* of 20% or more; potential tipping point for collapse of maize crop in some regions *(low confidence)*
Livestock in the tropics and subtropics	Increased heat-stress	Onset of persistent heat-stress *(medium confidence)*	Persistent heat-stress *likely.*

[START BOX 3.6 HERE]

Box 3.6: Economic Damages from Climate Change

Balancing of the costs and benefits of mitigation is challenging because estimating the value of climate change damages depends on multiple parameters whose appropriate values have been debated for decades (for example, the appropriate value of the discount rate) or that are very difficult to quantify (for example, the value of non-market impacts; the economic effects of losses in ecosystem services; and the potential for adaptation, which is dependent on the rate and timing of climate change and on the socioeconomic content) (see Cross-Chapter Box 5 in Chapter 2 for the definition of the social cost of carbon, and discussion of the economics of 1.5°C-consistent pathways and the social cost of carbon, including the impacts of inequality on the social cost of carbon).

Global economic damages of climate change are smaller under warming of 1.5°C than 2°C in 2100 (Warren et al., 2018c). The mean net present value of the costs of damages from warming in 2100 for 1.5°C and. 2°C (including costs associated with climate change-induced market and non-market impacts, impacts due to sea level rise, and impacts associated with large scale discontinuities) are $54 and $69 trillion, respectively, relative to 1961-1990.

Values of the social cost of carbon vary when tipping points are included. The social cost of carbon in the default setting of the Dynamic Integrated Climate-Economy (DICE) model increases from \$15/tCO_2 to \$116 (range 50-166)/tCO_2 when large-scale singularities or 'tipping elements'are incorporated (Y. Cai et al., 2016; Lemoine and Traeger, 2016). Lemoine and Traeger (2016) included optimization calculations that minimize welfare impacts resulting from the combination of climate change risks and climate change mitigation costs, showing that welfare is minimized if warming is limited to 1.5ºC. These calculations excluded the large health co-benefits that accrue when greenhouse gas emissions are reduced (Shindell 2018; Section 3.4.7.1)

The economic damages of climate change in the USA are projected to be large (Hsiang et al., 2017; Yohe, 2017). Although not specifically related to 1.5˚C warming, Hsiang et al. (2017) concluded that the USA could lose 2.3% Gross Domestic Product (GDP) per degree of global warming. Yohe (2017) calculated transient temperature trajectories from a linear relationship with contemporaneous cumulative emissions under a median no-policy baseline trajectory that brings global emissions to roughly 93 GtCO_2 per year by the end of the century (Fawcett et al., 2015), with 1.75˚C per 1000 GtCO_2 as the median estimate (Yohe, 2017). Associated aggregate economic damages in decadal increments through the year 2100 are estimated in terms of the percentage loss of GDP at the median, 5th percentile, and 95th percentile transient temperature (Hsiang et al., 2017). The results for the baseline no-policy case indicate that economic damages along median temperature change and median damages (median-median) reach 4.5% of GDP by 2100, with an uncertainty range of 2.5% and 8.5% resulting from different combinations of temperature change and damages. Avoided damages from achieving a 1.5ºC temperature limit along the median-median case is nearly 4% (range 2.0 – 7.0%) by 2100. Avoided damages from achieving a 2ºC temperature limit is lower: 3.5% (range 1.8% - 6.5%). Avoided damages from achieving 1.5ºC vs. 2ºC is modest; it is about 0.35% (range 0.20 – 0.65%) by 2100. The values of achieving either temperature limit do not diverge significantly until 2040, when their difference tracks between 0.05% and 0.13%; the differences between the two temperature targets begin to diverge substantially in the second half of the century.

[END BOX 3.6 HERE]

3.6 Implications of different 1.5ºC and 2ºC pathways

This section provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C global warming. Some of these aspects are also addressed in more detail in the Cross-Chapter Boxes 7 and 8 in this Chapter.

3.6.1 Gradual vs overshoot in 1.5ºC scenarios

All 1.5°C scenarios from Chapter 2 include some overshoot above 1.5°C global warming during the 21st century (Chapter 2, Cross-Chapter Box 8 in this Chapter). The level of overshoot may also depend on natural climate variability. An overview of possible outcomes of a 1.5°C-consistent mitigation scenarios for changes in physical climate at the time of overshoot and by 2100 is provided in the Cross-Chapter Box 8 on "1.5°C warmer worlds". Cross-Chapter Box 8 also highlights the implications of overshoots.

3.6.2 Non-CO_2 implications and projected risks of mitigation pathways

3.6.2.1 Risks arising from Land use changes in mitigation pathways

In mitigation pathways, land use change is affected by many different mitigation options. First of all, mitigation of non-CO_2 emissions from agricultural production can shift agricultural production between regions via trade of agricultural commodities. Secondly, protection of carbon rich ecosystems such as tropical forests constrains area for agricultural expansion. Thirdly, also demand side mitigation measures such as les consumption of resource intensive commodities (animal products) or food waste reductions reduce pressure on land (Popp et al., 2017; Rogelj et al., 2018). Finally, Carbon Dioxide Removal (CDR) is a key component of most, but not all mitigation pathways presented in the literature to date which constrain warming to 1.5°C or 2°C. Typically, CDR measures that require land can include Bioenergy with Carbon Capture and Storage (BECCS), afforestation and reforestation (AR), soil carbon sequestration, direct air capture, biochar, and enhanced weathering (see Cross-Chapter Box 7 in this Chapter). These potential methods are assessed in Section 4.3.7.

In cost-effective Integrated Assessment Modelling (IAM) pathways recently developed to be consistent with limiting warming to 1.5°C, use of CDR in the form of BECCS and AR are also fundamental elements (Chapter 2; Popp et al., 2017; Hirsch et al., 2018; Rogelj et al., 2018; Seneviratne et al., 2018c). The land-use footprint of CDR deployment in 1.5°C-consistent pathways can be substantial (Section 2.3.4, Figure 2.11), even though IAMs predominantly rely on second generation biomass and assume future productivity increases in agriculture.

A body of literature has explored potential consequences of large scale use of CDR. In this case, the corresponding land footprint by the end of the century could be extremely large, with estimates including: up to 18% of the land surface being used (Wiltshire and Davies-Barnard, 2015); vast acceleration of the loss of primary forest and natural grassland (Williamson, 2016) leading to increased greenhouse gas emissions (P. Smith et al., 2013, Smith et al., 2015); potential loss of up to 10% of the current forested lands to biofuels (Yamagata et al., 2018). Other estimates reach 380-700 Mha/21-64% of current arable cropland (Section 4.3.7); while Boysen et al. (2017) find that in a scenario in which emission reductions were sufficient only to limit warming to 2.5ºC, use of CDR to limit warming further to 1.7ºC would result in conversion of 1.1-1.5

Gha of land – implying enormous losses of both cropland and natural ecosystems (Boysen et al., 2017). Newbold et al. (2015) find that biodiversity loss in the scenario Representative Concentation Pathway (RCP)2.6 could be greater than that in RCP4.5 and RCP6.0, in which there is more climate change but less land use change. Risks to biodiversity conservation and agricultural production are therefore projected to result from large-scale bioenergy deployment pathways (P. Smith et al., 2013; Tavoni and Socolow, 2013). One study explores an extreme mitigation strategy encouraging biofuel expansion sufficient to limit warming to 1.5ºC, which finds that this is more disruptive to land use and crop prices than the climate change impacts of +2.0 ºC world which has a larger climate signal and lower mitigation requirement (Ruane et al., 2018). However, it should again be emphasized that many of the pathways explored in Chapter 2 of this report follow strategies that explore how to reduce these issues. Chapter 4 provides an assessment of the land footprint of various CDR technologies (Section 4.3.7).

The degree to which BECCS would have these large land-use footprints depends on the source of the bioenergy used, and the scale at which BECCS is deployed. Whether there is competition with food production and biodiversity depends on the governance of land use, agricultural intensification, trade, demand for food (in particular meat), feed and timber, and the context of the whole supply chain (Section 4.3.7, Fajardy and Mac Dowell, 2017; Booth, 2018; Sterman et al., 2018).

The more recent literature reviewed in Chapter 2 explores pathways which limit warming to 2°C or below and achieve a balance between sources and sinks of CO_2, using BECCS that relies on second-generation (or even third generation) biofuels, or which relies on changes in diet or more generally, management of food demand, or CDR options such as forest restoration (see Chapter 2, Bajželj et al., 2014). Overall this literature explores how to reduce the issues of competition for land with food production and with natural ecosystems (in particular forests) (see Cross-Chapter Box 1 in Chapter 1, van Vuuren et al., 2009; Haberl et al., 2010, 2013; Bajželj et al., 2014; Daioglou et al., 2016; Fajardy and Mac Dowell, 2017).

Some IAMs manage this transition by effectively protecting carbon stored on land and focussing on the conversion of pasture area into both forest area and bioenergy cropland. Some IAMs explored 1.5°C consistent pathways with demand side measures (such as dietary changes) and efficiency gains such as agricultural changes (Sections 2.3.4, 2.4.4) which lead to a greatly reduced CDR deployment and consequently land use impacts (van Vuuren et al., 2018). However, in reality whether this CDR (and more broadly, bioenergy in general) has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Obersteiner et al., 2016; Bertram et al., 201; Humpenöder et al. 2018; Section 2.3.4).

Rates of sequestration of 3.3 GtC/ha require 970 Mha of afforestation and reforestation (Smith et al., 2015). Humpenöder et al. (2014) estimates that in least cost pathways afforestation would cover 2800 Mha by the end of the century to constrain warming to 2°C. Hence, the amount of land considered if least-cost mitigation is implemented by afforestation and reforestation could be up to 3 to 5 times greater than that required by BECCS, depending on the forest management used. However, not all of the land footprint of CDR need be in competition with biodiversity protection. Where reforestation is the restoration of natural ecosystems, this benefits both carbon sequestration and conservation of biodiversity and ecosystem services (Section 4.3.7) and can contribute to the achievement of the Aichi targets under the Convention on Biological Diversity (CBD) (Leadley et al., 2016). However, reforestation is often not defined in this way (Stanturf et al., 2014, Section 4.3.8) and the ability to deliver biodiversity benefits is strongly dependent on the precise nature of the reforestation, which has many different interpretations in different contexts and can often include agroforestry rather than restoration of pristine ecosystems (Pistorious and Kiff, 2017).

However, 'natural climate solutions' defined as conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands is estimated to have the potential to provide 37% of cost-effective CO_2 mitigation needed through 2030 consistent with a >66% chance of holding warming to below 2°C (Griscom et al., 2017).

Any reductions in agricultural production driven by climate change and/or land management decisions related to CDR may (e.g., Nelson et al., 2014a; Dalin & Rodríguez-Iturbe, 2016) or may not (Muratori et al., 2016) affect food prices. However, these studies do not consider the deployment of second-generation bioenergy crops (instead of first-generation) for which the land footprint can be much smaller. Irrespective of any mitigation-related issues, in order for ecosystems to adapt to climate change, land use would also need to be carefully managed to allow biodiversity to disperse to areas that become newly climatically suitable for it Section 3.4.1) as well as protecting the areas where the climate still remains suitable in the future. This implies a need for a considerable expansion of the protected area network (Warren et al., 2018a), either to protect existing natural habitat or to restore it (perhaps through reforestation, see above). At the same time, adaptation to climate change in the agricultural sector (Rippke et al., 2016) can require transformational as well as new approaches to land use management; whilst in order to meet the rising future food demand of a growing human population, additional land is projected to be needed to be brought into production, unless there are large increases in agricultural productivity (Tilman et al., 2011) yet future rates of deforestation may be underestimated in the existing literature (Mahowald et al., 2017a). Hence, reforestation may be associated with significant co-benefits if implemented so as to restore natural ecosystems (*high confidence*).

3.6.2.2 Biophysical feedbacks on regional climate associated with land use changes

Changes in the biophysical characteristics of the land surface are known to have an impact on local and regional climates through changes in albedo, roughness, evapotranspiration and phenology that can lead to a change in temperature and precipitation. This includes changes in land use through agricultural expansion/intensification (e.g., Mueller et al., 2016) or reforestation/revegetation endeavours (e.g., Feng et al., 2016; Sonntag et al., 2016; Bright et al., 2017) and changes in land management (e.g., Luyssaert et al., 2014; Hirsch et al., 2017) that can involve double cropping (e.g., Jeong et al., 2014; Mueller et al., 2015; Seifert and Lobell, 2015), irrigation (e.g., Lobell et al, 2009; Sacks et al., 2009; Cook et al., 2011; Qian et al., 2013; de Vrese et al., 2016; Pryor et al., 2016; Thiery et al., 2017), no-till farming and conservation agriculture (e.g., Lobell et al., 2006; Davin et al., 2014) and wood harvest (e.g., Lawrence et al., 2012). Hence, the biophysical impacts of land use changes are an important topic to assess in the context of low-emissions scenarios (e.g., (van Vuuren et al., 2011b), in particular for 1.5°C warming levels (see also Cross-Chapter Box 7 in this Chapter).

The magnitude of the biophysical impacts is potentially large for temperature extremes. Indeed, both changes induced by modifications in moisture availability and irrigation, or by changes in surface albedo, tend to be larger (i.e., stronger cooling) for hot extremes than for mean temperatures (e.g., (Seneviratne et al., 2013; Davin et al., 2014; Wilhelm et al., 2015; Hirsch et al., 2017; Thiery et al., 2017). The reasons for reduced moisture availability are related to a strong contribution of moisture deficits to the occurrence of hot extremes in mid-latitude regions (Mueller and Seneviratne, 2012; Seneviratne et al., 2013). In the case of surface albedo, cooling associated with higher albedo (e.g., in the case of no-till farming) is more effective at cooling hot days because of the higher incoming solar radiation for these days (Davin et al., 2014). The overall effect of either irrigation or albedo has been found to be at the most of the order of ca. 1–2°C regionally for temperature extremes. This can be particularly important in the context of low-emissions scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas forcing (Hirsch et al., 2017, Figure 3.21; Seneviratne et al., 2018a).

In addition to the biophysical feedbacks from land use change and land management on climate, there are potential consequences for particular ecosystem services. This includes climate change induced changes in crop yield (e.g., (Schlenker and Roberts, 2009; van der Velde et al., 2012; Asseng et al., 2013, 2015; Butler and Huybers, 2013; Lobell et al., 2014) which may be further exacerbated by competing demands for arable land between reforestation mitigation activities, growing crops for BECCS (Chapter 2), increasing food production to support larger populations or urban expansion (e.g., see review by Smith et al., 2010). In particular, some land management practices may have further implications for food security where some regions may have increases or decreases in yield when ceasing tillage (Pittelkow et al., 2014).

We note that the biophysical impacts of land use in the context of mitigation pathways is an emerging research topic. This topic as well as the overall role of land use change for climate change projections and socio-economic pathways will be addressed in depth in the upcoming IPCC Special Report on Climate Change and Land due in 2019.

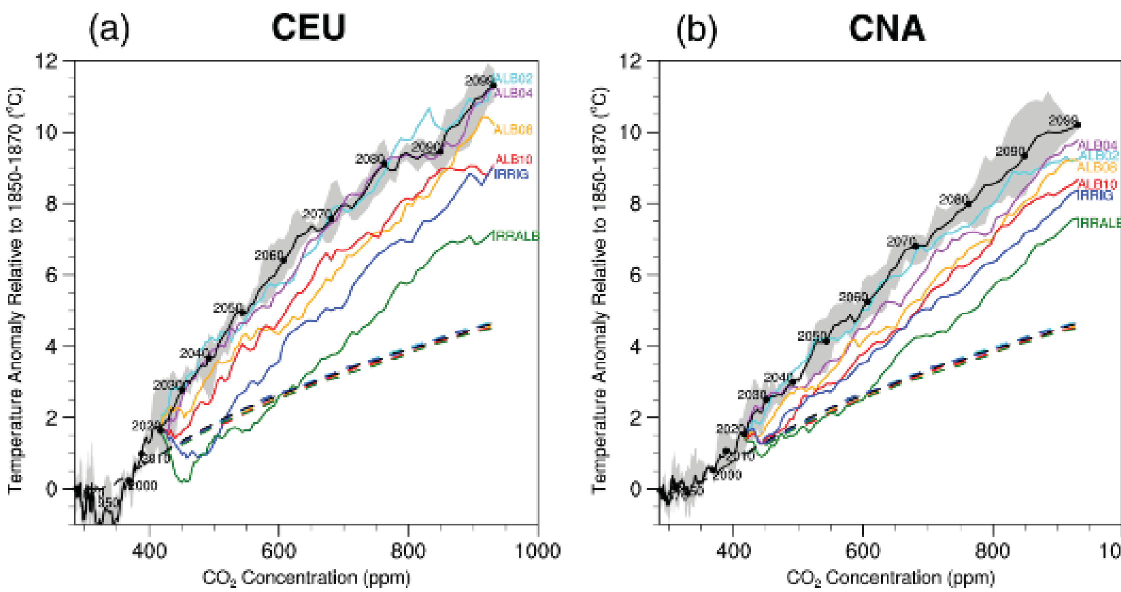

Figure 3.19: Regional temperature scaling with carbon dioxide (CO_2) concentration (ppm) over 1850 to 2099 for two different regions as defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX): Central Europe (CEU) (a) and Central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850–1870 and units are degrees Celsius. The black line in all panels denotes the 3-member control ensemble mean with the grey shaded regions corresponding to the ensemble range. The colored lines correspond to the 3-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo + 0.08 (orange), albedo +0.10 (red), irrigation on (blue), and irrigation with albedo +0.10 (green). Adapted from Hirsch et al. (2017).

3.6.2.3 *Atmospheric compounds (aerosols and methane)*

There are multiple pathways that could be used to limit anthropogenic climate change, and the details of the pathways will change the climate impacts on humans and ecosystems. Anthropogenic driven changes in aerosols cause important modifications to global climate (Bindoff et al., 2013a; Boucher et al., 2013b; P. Wu et al., 2013; Sarojini et al., 2016; H. Wang et al., 2016). Enforcement of strict air quality policies may lead to a large decrease in cooling aerosols emissions in the next few decades. These aerosol emission reductions may cause a comparable warming to the increase in greenhouse gases by mid-21st century in the low CO_2 pathways (Kloster et al., 2009; Navarro et al., 2017), especially in the low CO_2 pathways (Cross Chapter Box 1; Sections 2.2.2 and 2.3.1). Because aerosol effects on the energy budget are regional, strong regional changes in precipitation changes from aerosols may occur if aerosols emissions are reduced for air quality or as a co-benefit from switches to sustainable energy sources (H. Wang et al., 2016). Thus regional impacts, especially on precipitation, are very sensitive to 1.5ºC-consistent pathways (Z. Wang et al., 2017).

Pathways which rely strong on reductions in methane (CH_4) versus CO_2 will reduce warming in the short-term because methane is such a stronger and shorter-lived greenhouse gas, but will be warmer in the long term because of the much longer residence time of CO_2 (Myhre et al., 2013; Pierrehumbert, 2014). In addition, the dominant loss mechanism for methane is atmospheric photooxidation. This conversion modifies ozone formation and destruction in the troposphere and stratosphere, and therefore modifies the contribution of ozone to radiative forcing, as well as feedbacks onto the oxidation rate of methane itself (Myhre et al., 2013). Focusing on pathways and policies which both improve air quality and reduce climate impacts can serve to provide multiple co-benefits (Shindell et al., 2017), and these pathways are discussed in detail in Sections 4.3.7 and 5.4.1; and Cross Chapter Box 12 in Chapter 5.

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic carbon dioxide, but some compounds enhance uptake, while others reduce uptake (Ciais et al., 2013) (Section 2.6.2). While CO_2 emissions tend to encourage greater uptake of carbon by the land and the ocean (Ciais et al., 2013), methane emissions can enhance ozone pollution, depending on nitrogen oxides, volatile organic compounds, and other organic species concentrations, and ozone tends to reduce land productivity (Myhre et al., 2013; B. Wang et al., 2017). Aside from inhibiting land vegetation productivity, ozone may also alter the CO_2, CH_4 and nitrogen (N_2O) exchange at the land-atmosphere interface and transform the global soil system from a sink to a source of carbon (B. Wang et al., 2017). Aerosols and associated nitrogen-based compounds tend to enhance the uptake of carbon dioxide in land and ocean systems through the deposition of nutrients and modification of climate (Ciais et al., 2013; Mahowald et al., 2017b).

[START BOX Cross-Chapter Box 7]

Cross-Chapter Box 7: Land-Based Carbon Dioxide Removal, in Relation to 1.5°C Warming

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Climate and land form a complex system characterised by multiple feedback processes and the potential for non-linear responses to perturbation. Climate determines land cover and the distribution of vegetation affecting above and below ground carbon stocks. At the same time, land cover influences global climate through altered biogeochemical processes (e.g. atmospheric composition and nutrient flow into oceans), and regional climate through changing biogeophysical processes (including albedo, hydrology, transpiration and vegetation structure) (Forseth, 2010).

Greenhouse Gas (GHG) fluxes related to land use are reported in the Agriculture, Forestry and Other Land Use sector (AFOLU) and comprise about 25% (about 10–12 $GtCO_{2eq}yr^{-1}$) of anthropogenic GHG emissions (P. Smith et al., 2014). Reducing emissions from land use, and land use change are thus an important component of low-emissions mitigation pathways (Clarke et al., 2014), particularly as land-use emissions can be influenced by human actions such as deforestation, afforestation, fertilisation, irrigation, harvest, and other aspects of cropland, grazing land and livestock management (Paustian et al., 2006; Griscom et al., 2017; Houghton and Nassikas, 2018).

In the IPCC Fifth Assessment Report, the vast majority of scenarios assessed with a 66% or better chance of limiting global warming to 2°C by 2100 included Carbon Dioxide Removal (CDR) – typically about 10 $GtCO_2$ per year in 2100 or about 200–400 $GtCO_2$ over the course of the century (Smith et al., 2015; van Vuuren et al., 2016). These Integrated Assessment Model (IAM) results were predominately achieved by using bioenergy with carbon capture and storage (BECCS) and/or afforestation and reforestation (AR). Virtually all scenarios that either limit peak or end-of-century warming to 1.5°C also use land intensive CDR technologies (Rogelj et al., 2015; Holz et al., 2017; Kriegler et al., 2017; Fuss et al., 2018; van Vuuren et al., 2018). Again, afforestation and reforestation (AR) (Sections 2.3, 4.3.7); and BECCS (Sections 4.3.2., 4.3.7) predominate. Other CDR options such as the application of biochar to soil, soil carbon sequestration, and enhanced weathering (Section 4.3.7) are not yet widely incorporated in IAMs, but their deployment would also necessitate the use of land and/or changes in land management.

IAMs provide a simplified representation of land use and, with only a few exceptions, they do not include biophysical feedback processes (e.g. albedo and evapotranspiration effects) (Kreidenweis et al., 2016) despite the importance of these processes for regional climate, in particular hot extremes (Seneviratne et al., 2018c; section 3.6.2.2). The extent, location, and impacts of large-scale land-use change described by existing IAMs can also be widely divergent depending on model structure, scenario parameters, modelling objectives, and assumptions (including land availability and productivity) (Prestele et al., 2016; Alexander et al., 2017; Popp et al., 2017; Seneviratne et al., 2018d). Despite these limitations, IAM scenarios effectively highlight the extent and nature of potential land-use transitions implicit in limiting warming to 1.5^{o}C .

Cross-Chapter Box 7 Table 1, presents a comparison of the five CDR options assessed in this report. This illustrates that if deployed at a scale -e.g. 12 $GtCO_2yr^{-1}$ in 2100-, BECCS and AR would have a substantial land and water footprint. Wether this footprint results in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, limit the expansion of agriculture at the expense of natural ecosystems, and increase agriculture productivity (Bonsch et al., 2016; Obersteiner et al., 2016; Bertram et al., 2018; Humpenöder et al., 2018). In comparison, the land and water footprints of enhanced weathering, soil carbon sequestration and biochar application are expected to be far less per $GtCO_2$ sequestered. These options may offer potential co-benefits by providing an additional source of nutrients or reducing N_2O emissions, but they are also associated with potential side-effects. Enhanced weathering would require massive mining activity, and providing feedstock for biochar would require additional land, even though a proportion of the required biomass is expected to come from residues (Woolf et al., 2010; Smith, 2016). For the terrestrial CDR options permanence and saturation are important considerations, making their viability and long-term contributions to carbon reduction targets uncertain.

The technical, political, and social feasibility of scaling up and implementing land-intensive CDR technologies (Cross-Chapter Box 3 in Chapter 1) is recognised to present considerable potential barriers to future deployment (Boucher et al., 2013a; Fuss et al., 2014, 2018; Anderson and Peters, 2016; Williamson, 2016; Vaughan and Gough, 2016; Minx et al., 2017, 2018; Nemet et al., 2018; Strefler et al., 2018; Vaughan et al., 2018). To investigate the implications of restricting CDR options should these barriers prove difficult to overcome IAM studies (Section 2.3.4) have developed scenarios that limit (either implicity or explicity) the use of BECCS and bioenergy (Krey et al., 2014; Bauer et al., 2018; Rogelj et al., 2018), or BECCS and afforestation (Strefler et al., 2018). Alternative strategies to limit future reliance on CDR have also been examined including increased electrification, agricultural intensification, behavioral change and dramatic improvements in energy and material efficiency (Bauer et al., 2018; Grübler, 2018; van Vuuren et al., 2018). Somewhat counterintuitively, scenarios that seek to limit the deployment of BECCs may result in increased land use through greater deployment of bioenergy, and afforestation (Krey et al., 2014; Krause et al., 2017; Bauer et al., 2018; Rogelj et al., 2018) (Chapter 2, Box 2.1). Scenarios aiming to minimize the total human land footprint (including land for food, energy, and climate mitigation) also result in land use change, for example by postulating that increases in agricultural efficiency and changes in diet can enable land use, for example by postulating that increases in agricultural efficiency and changes in diet can enable land use switching from food crop production to energy crop production without altering the overall agricultural area (Grübler, 2018).

The impacts of changing land use are highly context, location and scale dependent (Robledo- Abad et al., 2017). The supply of biomass for CDR (e.g. energy crops) has received particular attention. The literature identifies regional examples of where the use of land to produce biofuels might be sustainably increased (Jaiswal et al., 2017), where biomass markets could contribute to the provision of ecosystem services (Dale et al., 2017), and where bioenergy could increase the resilience of production systems and contribute to rural development (Kline et al., 2017). Yet studies of global biomass potential provide only limited insight into the local feasibility of supplying large quantities of biomass on a global scale (Slade et al., 2014). Concerns about large scale use of biomass for CDR include a range of potential consequences including: greatly increased demand for freshwater use, increased competition for land, loss of biodiversity and/or impacts on food security (Heck et al., 2018; Section 3.6.2.1). The short versus long term carbon impacts of substituting biomass for fossil fuels (in large part determined by feedstock choice) also remain a source of contention (Schulze et al., 2012; Jonker et al., 2014; Booth, 2018; Sterman et al., 2018).

AR can also present trade-offs between biodiversity, carbon sequestration and water use, and has a higher land footprint per ton of CO_2 removed (Cunningham et al., 2015; Naudts et al., 2016; Smith et al., 2018). For example, changing forest management to strategies towards faster growing species, greater residue extraction, and shorter rotations may have a negative impact on biodiversity (de Jong et al., 2014). In contrast, reforestation of degraded land with native trees can have substantial benefits for biodiversity (Section 3.6). Despite these constraints the potential for increased carbon sequestration through improved land stewardship measures is considered to be substantial (Griscom et al., 2017).

Evaluating the synergies and trade-offs between mitigation and adaptation actions, resulting land and climate impacts, and the myriad issues related to land-use governance will be essential to better understand the future role of CDR technologies. This will be further addressed in the IPCC Special Report on Climate Change and Land (SRCCL) due to be published in 2019.

Key messages:

Cost-effective strategies to limit peak or end-of-century warming to 1.5°C all include enhanced GHG removals in the AFOLU sector as part of their portfolio of measures (*high agreement, robust evidence*).

Large-scale deployment of land-based CDR would have far reaching implications for land and water availability (*high agreement, robust evidence*). This may impact food production, biodiversity and the provision of other ecosystem services (*high agreement, medium evidence*)

The impacts of deploying land-based CDR at scale can be reduced if a wider portfolio of CDR options is deployed, and if increased mitigation effort focusses on strongly limiting demand for land, energy and material resources including lifestyle and dietary change (*high agreement, medium evidence*).

Afforestation and reforestation may be associated with significant co-benefits if implemented appropriately, but feature large land water footprints if deployed at scale (*medium agreement, medium evidence*).

Cross-Chapter Box 7, Table 1: Comparison of land-based carbon removal options

Sources: [a] assessed ranges by Fuss et al. (2018); see Figures in Section 4.3.7 for full literature range; [b] based on 2100 estimate for mean potentials by (Smith et al., 2015). Note that biophysical impacts of land-based CDR options besides albedo changes (e.g., through changes in evapotranspiration related to irrigation or land cover/use type) are not displayed.

Option	**Potentials [a]**	**Cost [a]**	**Required land [b]**	**Required water [b]**	**Impact on nutrients [b]**	**Impact on albedo [b]**	**Saturation & permanence [a]**
	$GtCO_2$ y^{-1}	*\$ per tCO_2*	*Mha $GtCO_2^{-1}$*	*km^3 $GtCO_2^{-1}$*	*Mt N, P, K y^{-1}*	*No units*	*No units*
BECCS	0.5-5	100-200	31-58	60	Variable	Variable, depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g., no-till farming for crops)	Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration
Afforestation & Reforestation	0.5-3.6	5-50	80	92	0.5	Negative; or reduced GHG benefit where not negative	Saturation of forests; vulnerable to disturbance; post-AR forest management essential
Enhanced Weathering	2-4	50-200	3	0.4	0	0	Saturation of soil; residence time from months to geological time scale

Biochar	0.3-2	30-120	16-100	0	N:8.2, P:2.7, K:19.1	0.08–0.12	Mean residence times between decades to centuries depending on soil type, management, and environmental conditions
Soil Carbon Sequestration	2.3-5	0-100	0	0	N:21.8, P:5.5, K:4.1	0[1]	Soil sinks saturate and can reverse if poor management practices were to resume

[END BOX Cross-Chapter Box 7]

3.6.3 Implications beyond the end of the century

3.6.3.1 Sea ice

Sea ice is often cited as a tipping point in the climate system (Lenton, 2012). Detailed modelling of sea ice (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011), however, suggests that summer sea ice can return within a few years after its artificial removal for climates in the late 20th and early 21st centuries. Further studies (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) remove sea ice by raising CO_2 concentrations and study subsequent regrowth by lowering CO_2. These studies also suggest changes in Arctic sea ice are neither irreversible nor exhibit bifurcation behavior. It is therefore plausible that the extent of Arctic sea ice may quickly re-equilibrate to end-of-century climate in the event of an overshoot scenario.

3.6.3.2 Sea level

The impacts of policy decisions related to anthropogenic climate change will have a profound impact on sea level not only for the remainder of this century but for many millennia to come (Clark et al., 2016). On these long timescales, 50 m of sea level rise are potentially possible (Clark et al., 2016). While it is *virtually certain* that sea level will continue to rise well beyond 2100, the amount of rise depends on future cumulative emissions (Church et al., 2013) as well as their profile over time (Bouttes et al., 2013; Mengel et al., 2018). Marzeion et al. (2018) find that 28–44% of present-day glacier volume is unsustainable in the present-day climate, so that it would eventually (over the course of a few centuries) melt, even if there were no further climate change. Some components of sea level rise, such as thermal expansion, are only reversible on centennial timescales (Bouttes et al., 2013; Zickfeld et al., 2013), while the contribution from ice sheets may not be reversible under any plausible future scenario (see below).

Based on the sensitivities summarized by Levermann et al. (2013), the contributions of thermal expansion (0.20–0.63 m $°C^{-1}$) and glaciers (0.21 m $°C^{-1}$ falling at higher degrees of warming mostly because of the depletion of glacier mass, with a possible total of ~0.6 m) amount to 0.5–1.2 m and 0.6–1.7 m in 1.5 and 2°C warmer worlds, respectively. The bulk of Sea Level Rise (SLR) on greater than centennial timescales will therefore be contributed by the two continental ice sheets of Greenland and Antarctica, whose existence is threatened on multi-millennial timescales.

For Greenland, where melting from the ice sheet's surface is important, a well-documented instability exists where the surface of a thinning ice sheet encounters progressively warmer air temperatures that further promote melt and thinning. A useful indicator associated with this instability is the threshold at which annual mass loss from the ice sheet by surface melt exceeds mass gain by snowfall. Previous estimates (Gregory and

Huybrechts, 2006) put this threshold about 1.9ºC to 5.1°C above preindustrial period. More recent analyses, however, suggest that this threshold sits between 0.8ºC and 3.2°C with a best estimate at 1.6°C (Robinson et al., 2012). The continued decline of the ice sheet after this threshold has been passed is highly dependent on future climate and varies between about 80% loss after 10,000 years to complete loss after as little as 2000 years (contributing ~6 m to SLR).

The Antarctic ice sheet, in contrast, loses the mass gained by snowfall as outflow and subsequent melt to the ocean (either directly from the underside of floating ice shelves or indirectly by the melt of calved icebergs). The long-term existence of this ice sheet is also affected by a potential instability (the Marine Ice Sheet Instability, MISI), which links outflow (or mass loss) from the ice sheet to water depth at the grounding line (the point at which grounded ice starts to float and becomes an ice shelf) so that retreat into deeper water (the bedrock underlying much of Antarctica slopes downwards towards the centre of the ice sheet) leads to further increases in outflow and promotes yet further retreat (Schoof, 2007). More recently, a variant on this mechanism has been postulated in which an ice cliff forms at the grounding line which retreats rapidly though fracture and iceberg calving (DeConto and Pollard, 2016). There is a growing body of evidence (Golledge et al., 2015; DeConto and Pollard, 2016) that large-scale retreat may be avoided in emission scenarios such as Representative Concentration Pathway (RCP)2.6 but that higher-emission RCP scenarios could lead to the loss of the West Antarctic ice sheet and sectors in East Antarctica, although the duration (centuries or millennia) and amount of mass loss during such as collapse is highly dependent on model details and no consensus yet exists. Current thinking (Schoof, 2007) suggests that retreat may be irreversible, although a rigorous test has yet to be made. In this context, overshoot scenarios, especially of higher magnitude or longer duration, could be anticipated to increase the risk of such irreversible retreat.

The assessment also noted that the collapse of marine sectors of the Antarctic ice sheet could lead to Global Mean Sea Level (GMSL) rise above the likely range, and that there was *medium confidence* that this additional contribution 'would not exceed several tenths of a metre during the 21st century' (Church et al., 2013).

The multi-centennial evolution of the Antarctic ice sheet is considered in papers by DeConto and Pollard (2016) and Golledge et al. (2015). Both suggest that RCP2.6 is the only RCP scenario leading to long-term contributions to GMSL of below 1.0 m. The long-term committed future of Antarctica (and GMSL contribution at 2100) are complex and require further detailed process-based modelling, however a threshold in this contribution may be present close to 1.5ºC.

3.6.3.3 *Permafrost*

The slow rate of permafrost thaw introduces a lag between the transient degradation of near-surface permafrost and contemporary climate, so that the equilibrium response is expected to be 25–38% greater than the transient response simulated in climate models (Slater and Lawrence, 2013). The long-term, equilibrium Arctic permafrost loss to global warming is analyzed by Chadburn et al. (2017). They use an empirical relation between recent mean annual air temperatures and the area underlain by permafrost coupled to CMIP5 stabilization projections to 2300 for RCP2.6 and RCP4.5. Their estimate of the sensitivity of permafrost to warming is 2.9–5.0 million km^2 $°C^{-1}$ (1 standard deviation confidence interval), which suggests that stabilizing climate at 1.5°C as opposed to 2°C would reduce the area of eventually permafrost loss by roughly 2 million km^2 (stabilizing at 56–83% as opposed to 43–72% of 1960–1990 levels). This work combined with the assessment of Collins et al. (2013) on the link of global warming and permafrost loss, leads to the assessment that permafrost extent would be appreciably greater in a 1.5°C world compared to a

2°C world (*medium confidence*, *limited evidence*).

3.7 Knowledge gaps

Most scientific literature specific to global warming of 1.5°C is only just emerging. This has led to differences in the amount of information available and gaps across the various sections of this chapter. In general, the number of impact studies specifically focused on 1.5°C lags behind climate change projections in general, due in part to the dependence of the former on the latter. There are also insufficient studies focusing on regional changes, impacts and consequences at +1.5°C and +2°C of global warming.

The following gaps have been identified with respect to tools, methodologies and understanding in the current scientific literature specific to Chapter 3. The gaps identified here are not comprehensive but highlight general areas for improved understanding, especially of global warming at 1.5°C as compared to 2°C and higher.

3.7.1 Gaps in Methods and Tools

- Regional and global climate model simulations for low-emission scenarios such as a 1.5°C world.
- Robust probabilistic models which separate the relatively small signal between 1.5°C versus 2°C from background noise, and which handle the many uncertainties associated with non-linearities, innovations, overshoot, local scales, latent or lagging responses in climate.
- Projections of risks under a range of climate and development pathways required to understand how development choices affect the magnitude and pattern of risks, and to provide better estimates of the range of uncertainties.
- More complex and integrated socio-ecological models for predicting the response of terrestrial ecosystems to climate and models which are increasingly capable of separating climate effects from those associated with human activities.
- Tools for informing local and regional decision-making especially when the signal is ambiguous at 1.5°C and/or reverses sign at higher levels of global warming.

3.7.2 Gaps in Understanding

Earth systems and 1.5°C:

- The cumulative effects of multiple stresses and risks (e.g., increased storm intensity interacting with sea level rise and the effect on coastal people; feedback on wetlands due to climate change and human activities).
- Feedbacks associated with changes in land use/cover for low-emissions scenarios, for example,

feedback from changes in forest cover, food production, and biofuel production, Bio-Energy with Carbon Capture and Storage (BECCS), and associated unquantified biophysical impacts.

- The distinct impacts of different overshoot scenarios depending on (a) the peak temperature of the overshoot, (b) the length of the overshoot period, and (c) the associated rate of change in global temperature over the time period of the overshoot.

Physical and chemical characteristics of a 1.5ºC world:

- Critical thresholds for extreme events (e.g., drought, inundation) between 1.5°C and 2°C, for different climate models and projections. All aspects of storm intensity and frequency as a function of climate change, especially for 1.5°C and 2°C worlds, and the impact of changing storminess on storm surge, damage and coastal flooding at regional and local scales.

- The timing and implications of the release of stored carbon in Arctic permafrost in a 1.5˚C world and for climate stabilization by the end of the century.

- Antarctic ice sheet dynamics, global sea level, and links between seasonal and year-long sea ice in both polar regions.

Terrestrial and freshwater systems

- The dynamics between climate change, freshwater resources, and socioeconomic impacts for lower levels of warming.

- How the health of vegetation is likely to change, carbon storage in plant communities and landscapes, and phenomena such as the fertilization effect.

- The risks associated with species' maladaptation in response to climatic changes (e.g., effect of late frosts), and questions associated with issues such as the consequences of species advancing their spring phenology in response to warming, and the interaction between climate change, range shifts and local adaptation in a 1.5°C world.

- The biophysical impacts of land use in the context of mitigation pathways.

Ocean Systems

- Deep sea processes and risks to deep sea habitats and ecosystems.

- Changes in ocean chemistry in a 1.5˚C world, including how decreasing ocean oxygen content, ocean acidification, and changes to activity of multiple ion species, will affect natural and human systems.

- How ocean circulation is changing towards a 1.5°C and 2°C world, for example, vertical mixing, deep ocean processes, currents, and their impacts on weather patterns at regional to local scales.

- The impacts of changing ocean conditions at 1.5˚C and 2˚C warming on food webs, disease, invading species, coastal protection, fisheries and human well-being, especially as organisms modify their biogeographical ranges within a changing ocean.

- Specific linkages between food security and changing coastal and ocean resources.

Human systems

- The impacts of global and regional climate change at 1.5°C on food distribution, nutrition, poverty, tourism, coastal infrastructure, and public health, particularly for developing nations.

- Health and well-being risks in the context of socio-economic and climate change at 1.5°C, especially in key areas such as occupational health, air quality and infectious disease.

- Micro-climates at urban/city scales and their associated risks for natural and human systems, within cities and interactions with surrounding areas. For example, current projections do not integrate adaptation to projected warming by taking into account cooling that could be achieved through a combination of revised building codes, zoning, and land use to build more reflective roofs and urban surfaces that reduce urban heat islands.

- Implications of climate change at 1.5°C on livelihoods and poverty, on rural communities, indigenous groups and marginalised people.

- The changing levels of risk in terms of extreme events (including storms and heat events), especially with respect to people being displaced or having to migrate away from sensitive and exposed systems such as small islands, low lying coasts and deltas.

Cross-Chapter Box 8: 1.5ºC Warmer Worlds

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Introduction

The Paris Agreement includes goals of stabilizing Global Mean Surface Temperature (GMST) well below 2˚C and 1.5°C above preindustrial period, in the longer term. There are several aspects, however, that remain open regarding what a '1.5°C warmer world' could be like, in terms of mitigation (Chapter 2) and adaptation (Chapter 4), as well as in terms of projected warming and associated regional climate change (Chapter 3), overlaid on anticipated and differential vulnerabilities (Chapter 5). **Alternative '1.5°C warmer worlds' resulting from mitigation and adaptation choices, as well as from climate variability (climate 'noise'), can be vastly different** as highlighted in this Cross-Chapter Box. In addition, the range of models underlying 1.5°C projections can be substantial and needs factoring in.

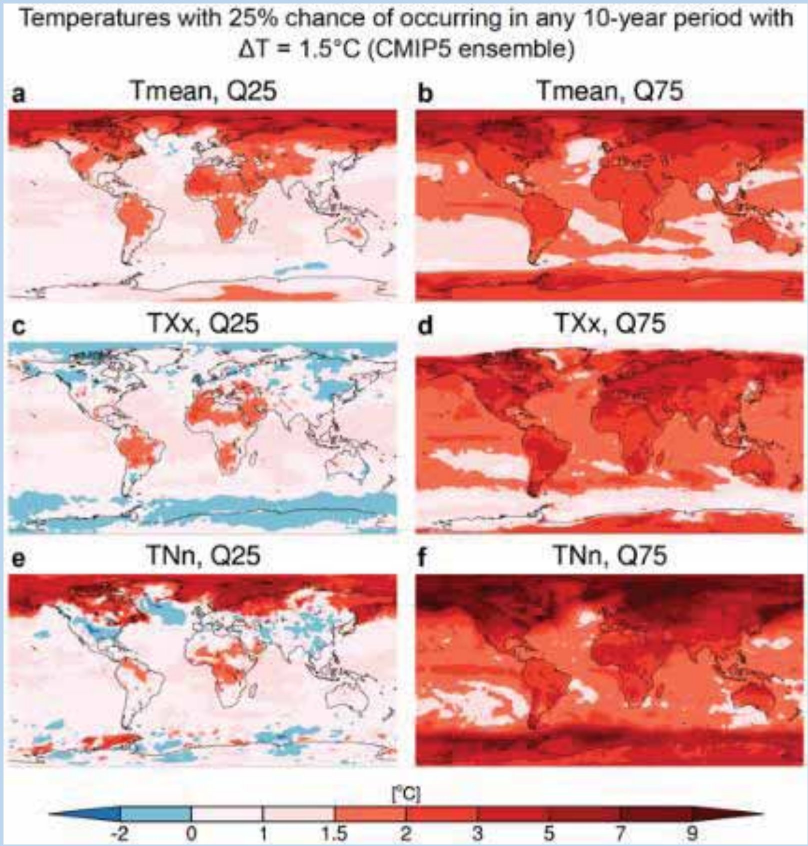
Key questions[3]:

- **What is a 1.5°C global mean warming, how is it measured, and what temperature increase does it imply for single locations and at specific times?** GMST corresponds to the globally averaged temperature of the Earth derived from point-scale ground observations or computed in climate models (Chapters 1 and 3). GMST is additionally defined over a given time frame, for example, averaged over a month, a year, or multiple decades. Because of climate variability, a climate-based global mean temperature typically needs to be defined over several decades (typically 20 or 30 years; Chapter 3, Section 3.2). Hence, whether or when global temperature reaches 1.5°C depends to some extent on the choice of preindustrial reference period, whether 1.5°C refers to total or human-induced warming, and which variables and coverage are used to define GMST change (Chapter 1). By definition, because GMST is an average in time and space, there will be locations and time periods in which 1.5°C warming is exceeded, even if the global mean temperature warming is at 1.5°C. In some locations, these differences can be particularly large (Cross-Chapter Box 8, Figure 1).

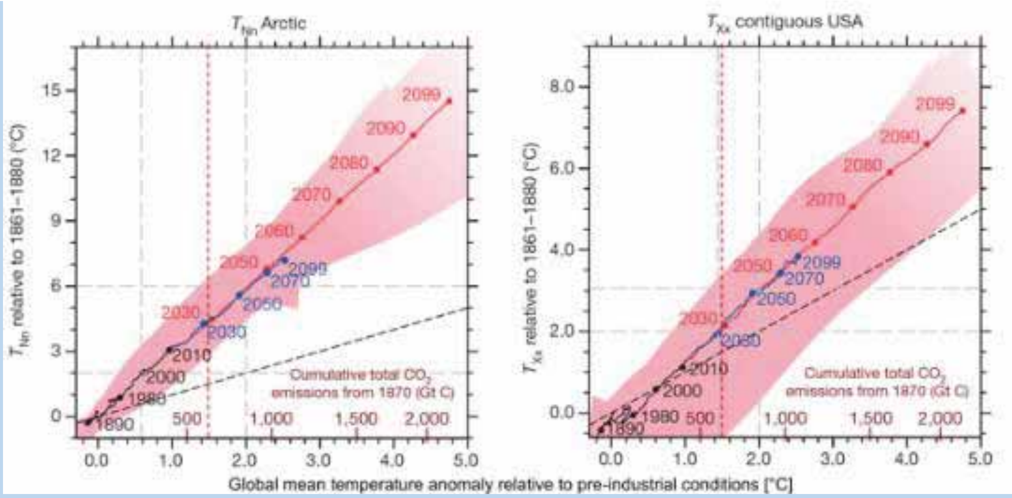
- **What is the impact of different climate models for projected changes in climate at 1.5°C global warming?** The range between single model simulations of projected regional changes at 1.5°C GMST warming can be substantial for regional responses (Chapter 3, Section 3.3). For instance, for the warming of cold temperature extremes in a 1.5°C warmer world, some model simulations project a 3°C warming and others more than 6°C warming in the Arctic land areas (Cross-Chapter Box 8, Figure 2). For warm temperature extremes in the contiguous United States, the range of model simulations includes colder temperatures than pre-industrial (-0.3°C) and a warming of 3.5°C (Cross-Chapter Box 8, Figure 2). Some regions display an even larger range (e.g., 1–5°C regional warming in hot extremes in Central Europe at 1.5°C warming, Chapter 3, Sections 3.3.1 and 3.3.2). This large spread is due both to modelling

[3]FOOTNOTE: Part of this discussion is based on Seneviratne et al. (2018b)

uncertainty and internal climate variability. While the range is large, it also highlights risks that can be avoided with near certainty in a 1.5°C warmer world compared to worlds at higher levels of warming (e.g., an 8°C warming in cold extremes in the Arctic is not reached at 1.5°C global warming in the multi-model ensemble, but could happen at 2°C global warming, Cross-Chapter Box 8, Figure 2). Inferred projected ranges of regional responses (mean value, minimum and maximum) for different mitigation scenarios from Chapter 2 are displayed in Cross-Chapter Box 8, Table 1.



Cross-Chapter Box 8, Figure 1: Range of projected realized temperature at 1.5°C (due to stochastic noise and model-based spread). Temperature with a 25% chance of occurrence at any location within 10-year time frames corresponding to GMST anomalies of 1.5°C (Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble). The plots display at each location the 25th percentile (Q25, left) and 75th percentile (Q75, right) values of mean temperature (Tmean), yearly maximum day-time temperature (TXx), yearly minimum night-time temperature (TNn), sampled from all time frames with GMST anomalies of 1.5°C in Representative Concentration Pathway (RCP)8.5 model simulations of the CMIP5 ensemble. From (Seneviratne et al., 2018b).



Cross-Chapter Box 8, Figure 2: Spread of projected multi-model changes in minimum annual night-time temperature (TNn) in the Arctic land (left) and in maximum annual day-time temperature (TXx) in the contiguous United States as a function of mean global warming in climate simulations. The multi-model range (due to model spread and internal climate variability) is indicated in red shading (minimum and maximum value based on climate model simulations). The multi-model mean value is displayed with solid red and blue lines for two emissions pathways (blue : Representative Concentration Pathway (RCP)4.5; red : RCP8.5). The dashed red line indicates projections for a 1.5°C warmer world. The dashed black line displays the 1:1 line. [after Seneviratne et al., 2016].

- **What is the impact of emissions pathways with, versus without, an overshoot?** All mitigation pathways projecting less than 1.5°C global warming over or at the end of the 21st century, include some probability of overshooting 1.5°C. These pathways include some time periods with higher warming than 1.5°C in the course of the coming decades and/or some probability of not reaching 1.5°C (Chapter 2; Section 2.2). This is inherent to the difficulty of limiting global warming to 1.5°C given that we are already very close to this warming level. The implications of overshooting are large for risks to natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (Chapter 3, Box 3.4). The chronology of emission pathways and their implied warming is also important for the more slowly evolving parts of the Earth system, such as those associated with sea level rise. In addition, for several types of risks, the rate of change may be of most relevance (Loarie et al., 2009; LoPresti et al., 2015) with thus potentially large risks in case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. On the other hand, if overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate, and unprecedented global efforts to mitigate GHGs are required (Cross-Chapter Box 8, Table 1; Chapter 4).

- **What is the probability of reaching 1.5°C global warming if emissions compatible with 1.5°C pathway are followed?** Emissions pathways in a "prospective scenario" (see Chapter 1, Section 1.2.3, and Cross-Chapter Box 1 in Chapter 1 on "Scenarios and pathways") compatible with a 1.5°C global warming, are determined based on their probability of reaching 1.5°C by 2100 (Chapter 2, Section 2.1) given current knowledge of the climate system response. These probabilities cannot be quantified precisely, but are typically 50–66% in 1.5°C-consistent pathways (Section 1.2.3). This implies a one-in-two to one-in-three probability that warming exceeds 1.5°C even under a 1.5°C-consistent pathway, including some possibility of being substantially over this value (generally about 5–10% probability, see Cross-Chapter Box 8, Table 1, and Seneviratne et al., 2018b). These alternative outcomes need to be factored into the decision-making process. To address this issue, "adaptive" mitigation scenarios are those in which emissions are continually adjusted to achieve a temperature goal (Millar et al., 2017). The set of dimensions involved in mitigation options (Chapter 4) is complex and need systemic approaches to be successful. Adaptive scenarios could be facilitated by the Global Stocktake mechanism established in the Paris Agreement, and thereby transfer the risk of higher-than-expected warming to a risk of faster-than-expected mitigation efforts. However, there are some limits to the feasibility of such approaches, because some investments (e.g. in infrastructure) are long-term and also because the actual departure from an aimed pathway will need to be detected against the backdrop of internal climate variability, typically over several decades (Haustein et al., 2017; Seneviratne et al., 2018b). Avoiding impacts that depend on atmospheric composition as well as GMST (Baker et al., 2018) would also require limits on atmospheric CO_2 concentrations in the event of a lower-than-expected GMST response.

- **How can the transformation towards a 1.5°C warmer world be implemented?** This can be achieved in a variety of ways such as decarbonizing the economy with an emphasis on demand reductions and sustainable lifestyles, or, alternatively, with an emphasis on large-scale technological solutions, amongst many other options (Chapter 2, Sections 2.3 and 2.4; Chapter 4, Sections 4.1 and 4.4.4). Different portfolios of mitigation measures come with distinct synergies and trade-offs for other societal objectives. Integrated solutions and approaches are required to achieve multiple societal objectives simultaneously (see Chapter 4, Section 4.5.4, for a set of synergies and trade-offs).

- **What determines risks and opportunities in 1.5°C warmer worlds?** The risks to natural, managed, and human systems in a 1.5°C warmer world will depend not only on uncertainties in the regional climate that results from this level of warming, but also very strongly upon the methods that humanity uses to limit warming to 1.5°C global warming. This is particularly the case for natural ecosystems and agriculture (see Cross-Chapter Box 7 in this Chapter and Chapter 4, Section 4.3.2). The risks to human systems will also depend on the magnitude and effectiveness of policies and measures implemented to increase resilience to the risks of climate change and will depend on development choices over coming decades that will influence underlying vulnerabilities and capacities of communities and institutions for responding and adapting.

- **Which aspects are not considered, or only partly considered, in the mitigation scenarios from Chapter 2?** These include biophysical impacts of land use, water constraints on energy infrastructure, and regional implications of choices of specific scenarios for tropospheric aerosol concentrations or the modulation of concentrations of short-lived climate forcers (Greenhouse Gases, Chapter 3, Section 3.6.3). Such aspects of development pathways need to be factored into comprehensive assessments of the regional implications of mitigation and adaptation measures. On the other hand, some of these aspects are assessed in Chapter 4 as possible options for mitigation and adaptation to a 1.5°C warmer world.

- **Are there commonalities to all 1.5°C warmer worlds?** Human-driven warming linked to CO_2 emissions is near irreversible over time frames of 1000 years or more (Matthews and Caldeira, 2008; Solomon et al., 2009). The global mean temperature of the Earth responds to the cumulative amount of CO_2 emissions. Hence all **1.5°C stabilization scenarios require both net CO_2 emissions and multi-gas CO_2-forcing-equivalent emissions to be zero** at some point (Chapter 2, Section 2.2). This is also the case for stabilization scenarios at higher levels of warming (e.g., at 2°C), the only difference would be the time at which the net CO_2 budget is zero.

- **Hence, a transition to decarbonisation of energy use is necessary in all scenarios**. It should be noted that **all scenarios of Chapter 2 include approaches for Carbon Dioxide Removal (CDR)** in order to achieve the net-zero CO_2 emission budget. **Most of these use Carbon Capture and Storage (CCS)** in addition to reforestation, to varying degrees (Chapter 4, Section 4.3.7). Some potential pathways to 1.5°C warming in 2100 would minimize the need for CDR (Obersteiner et al., 2018; van Vuuren et al., 2018). Taking into account the implementation of CDR, the CO_2-induced warming by 2100 is determined by the difference between the total amount of CO_2 generated (that can be reduced by early decarbonisation) and the total amount permanently stored out of the atmosphere, for example by geological sequestration (Chapter 4, Section 4.3.7).

- **What are possible storylines of 'warmer worlds' at 1.5°C vs higher levels of warming? Cross-Chapter Box 8, Table 2,** displays possible storylines based on the scenarios of Chapter 2, the impacts of Chapters 3 and 5, and the options of Chapter 4. These storylines are not intended to be comprehensive of all possible future outcomes. Rather, they are intended as plausible scenarios of alternative warmer worlds, with two storylines that either include stabilization at 1.5°C (Scenario 1) or close to 1.5°C (Scenario 2), and one missing this goal and consequently only including reductions of CO_2 emissions and efforts towards stabilization at higher temperatures (Scenario 3).

Summary:

There is no single '1.5°C warmer world'. Important aspects to consider (beside that of global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of global surface temperature at 1.5°C is achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks.

The implications of overshooting are large for risks to natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems. In addition, for several types of risks, the rate of change may be of most relevance with thus potentially large risks in case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate, and unprecedented global efforts to mitigate GHGs are required.

The time frame to initiate major mitigation measures is essential in order to reach a 1.5°C (or even a 2°C) global stabilization of climate warming (see consistent cumulative CO_2 emissions up to peak warming, Cross-Chapter Box 8, Table 1). If mitigation pathways are not rapidly activated, much more expensive and complex adaptation measures would have to be taken to avoid the impacts of higher global warming on the Earth system.

Cross-Chapter Box 8, Table 1: Different worlds resulting from 1.5°C and 2°C mitigation (prospective) pathways, including 66% (probable) best-case outcome, and 5% worst-case outcome, based on Chapter 2 scenarios and Chapter 3 assessments of changes in regional climate. Note that the pathway characteristics estimates are based on computations with the MAGICC model (Meinshausen et al., 2011) consistent with its set-up used in AR5 WGIII (Clarke et al., 2014), but are uncertain and will be subject to updates and adjustments (see Chapter 2 for details).

		B1.5_LOS (below 1.5°C with low overshoot) with 2/3 "probable best-case outcome"[a]	B1.5_LOS (below 1.5°C with low overshoot) with 1/20 "worst-case outcome"[b]	L20 (lower than 2°C) with 2/3 "probable best-case outcome"[a]	L20 (lower than 2°C) with 1/20 "worst-case outcome"[b]
General characteristics of pathway	**Overshoot > 1.5°C in 21[st] century[c]**	**Yes (51/51)**	**Yes (51/51)**	**Yes (72/72)**	**Yes (72/72)**
	Overshoot > 2°C in 21[st] century	**No (0/51)**	**Yes (37/51)**	**No (72/72)**	**Yes (72/72)**
	Cumulative CO_2 emissions up to peak warming (relative to 2016)[d]	610–760	590–750	1150–1460	1130–1470
	Cumulative CO_2 emissions up to 2100 (relative to 2016)[d] [$GtCO_2$]	170–560		1030–1440	
	Global GHG emissions in 2030[d] [$GtCO_2$ y-1]	19–23		31–38	
	Years of global net zero CO_2 emissions[d]	2055–2066		2082–2090	
Possible climate range at peak warming (regional+global)	**Global mean temperature anomaly at peak warming**	**1.7°C (1.66—1.72°C)**	**2.05°C (2.00—2.09°C)**	**2.11°C (2.05–2.17°C)**	**2.67°C (2.59–2.76°C)**
	Warming in the Arctic[e] (TNn[f])	4.93°C (4.36, 5.52)	6.02°C (5.12, 6.89)	6.24°C (5.39, 7.21)	7.69°C (6.69, 8.93)
	Warming in the Central North America[e] (TXx[g])	2.65°C (1.92, 3.15)	3.11°C (2.37, 3.63)	3.18°C (2.50, 3.71)	4.06°C (3.35, 4.63)
	Warming in Amazon region[e] (TXx)	2.55°C (2.23, 2.83)	3.07°C (2.74, 3.46)	3.16°C (2.84, 3.57)	4.05°C (3.62, 4.46)
	Drying in the Mediterranean region[e]	-1.11 (-2.24, -0.41)	-1.28 (-2.44, -0.51)	-1.38 (-2.58, -0.53)	-1.56 (-3.19, -0.67)
	Increase in heavy precipitation events[e] in Southern Asia[e]	9.94% (6.76, 14.00)	11.94% (7.52, 18.86)	12.68% (7.71, 22.39)	19.67% (11.56, 27.24)
Possible climate range in 2100 (regional+global)	**Global mean temperature warming in 2100**	**1.46°C (1.41—1.51°C)**	**1.87°C (1.81—1.94°C)**	**2.06°C (1.99—2.15°C)**	**2.66°C (2.56—2.76°C)**
	Warming in the Arctic[i] (TNn)	4.28°C (3.71, 4.77)	5.50°C (4.74, 6.21)	6.08°C (5.20, 6.94)	7.63°C (6.66, 8.90)
	Warming in Central North America[i] (TXx)	2.31°C (1.56, 2.66)	2.83°C (2.03, 3.49)	3.12°C (2.38, 3.67)	4.06°C (3.33, 4.59)
	Warming in Amazon region[i] (TXx)	2.22°C (2.00, 2.45)	2.76°C (2.50, 3.07)	3.10°C (2.75, 3.49)	4.03°C (3.62, 4.45)
	Drying in the Mediterranean region[i]	-0.95 (-1.98, -0.30)	-1.10 (-2.17, -0.51)	-1.26 (-2.43, -0.52)	-1.55 (-3.17, -0.67)
	Increase in heavy precipitation events in Southern Asia[i]	8.38% (4.63, 12.68)	10.34% (6.64, 16.07)	12.02% (7.41, 19.62)	19.72% (11.34, 26.95)

Cross-Chapter Box 8, Table 2: Storylines of possible worlds resulting from different mitigation options. The storylines build upon Cross-Chapter Box 8, Table 1, and the assessments of Chapters 1-5. These are only a few of possible storylines; their choice is for illustrative purposes.

Scenario 1 [one possible storyline among best-case scenarios]: **Mitigation: Early move to**	**In 2020, strong participation and support for the Paris Agreement and its ambitious goals for reducing CO_2 emissions by an almost unanimous international community led to a time frame for net-zero emissions that is compatible with halting of global temperature warming to 1.5°C by 2100.** There is strong participation in all major world regions at national, state and/or city levels. Transport is strongly decarbonized through a shift to electric vehicles, with

decarbonisation, decarbonisation designed to minimise land footprint, coordination and rapid action of world's nations towards 1.5°C goal by 2100 **Internal climate variability: Probable (66%) best-case outcome for global and regional climate responses.**	more cars with electric than combustion engines being sold by 2025 **(Chapter 2, Section 2.4.3; Chapter 4, Section 4.3.3)**. Several industry-sized plants for carbon capture and storage are installed and tested in the 2020s **(Chapter 2, Section 2.4.2; Chapter 4, Sections 4.3.4 and 4.3.7)**. Competition for land between bioenergy cropping, food production, and biodiversity conservation is minimised by sourcing bioenergy for carbon capture and storage from agricultural wastes, algae, and kelp farms (**Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2)**. Agriculture is intensified in countries with coordinated planning associated with a drastic decrease in food wastage **(Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2)**. This leaves many natural ecosystems relatively intact, supporting continued provision of most ecosystem services, although relocation of species toward higher latitudes and altitudes resulted in changes in local biodiversity in many regions, particularly in mountain, tropical coastal, and Arctic ecosystems **(Chapter 3, Section 3.4.3)**. Adaptive measures such as the establishment of corridors for the movement of species and parts of ecosystems become a central practice within conservation management **(Chapter 3, Section 3.4.3; Chapter 4, Section 4.3.2)**. The movement of species presents new challenges for resource management as novel ecosystems, and pests and disease, increase **(Cross-chapter Box 6 in Chapter 3)**. Crops are grown on marginal land and no-till agriculture deployed, and large areas are reforested with native trees **(Chapter 2, Section 2.4.4; Chapter 3, Section 3.6.2; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2)**. Societal preference for healthy diets reduces meat consumption and associated GHG emissions **(Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 6 in Chapter 3).** By 2100, global mean temperature is on average 0.5°C warmer than it was in 2018 **(Chapter 1, Section 1.2.1)**. Only a minor temperature overshoot occurs during the century **(Chapter 2, Section 2.2)**. In mid-latitudes, there are frequent hot summers and precipitation events tend to be more intense **(Chapter 3, Section 3.3)**. Coastal communities struggle with increased inundation associated with rising sea levels and more frequent and intense heavy rainfall **(Chapter 3, Sections 3.3.2 and 3.3.9; Chapter 5, Box 5.3 and Section 5.3.2; Cross-Chapter Box 12 in Chapter 5; Chapter 4, Section 4.3.2)**, and some respond by moving, in many cases, with consequences for urban areas. In the Tropics, in particular in mega-cities, there are frequent deadly heatwaves whose risks are reduced by proactive adaptation **(Chapter 3, Sections 3.3.1 and 3.4.8; Chapter 4, Section 4.3.8)**, overlaid on a suite of development challenges and limits in disaster risk management **(Chapter 4, Section 4.3.3; Chapter 5, Sections 5.2.1 and 5.2.2; Cross-Chapter Box 12 in Chapter 5)**. Glaciers extent decreases in most mountainous areas **(Chapter 3, Sections 3.3.5 and 3.5.4)**. Reduced Arctic sea ice opens up new shipping lanes and commercial corridors **(Chapter 3, Section 3.3.8; Chapter 4, Box 4.3)**. Small Island Developing States (SIDS), Coastal and low-lying areas have faced significant changes but have largely persisted in most regions **(Chapter 3; Sections 3.3.9 and 3.5.4; Box 3.5)**. The Mediterranean area becomes drier **(Chapter 3, Section 3.3.4 and Box 3.2)** and irrigation of crops expands, drawing the water table down in many areas **(Chapter 3, Section 3.4.6)**. The Amazon is reasonably well preserved (through avoided risk of possible large changes in regional temperature means and hot extremes and the probability of most extreme droughts **(Chapter 3, Sections 3.3.3, 3.3.4 and 3.4.3; Chapter 4, Box 4.3)** as well as through reduced deforestation **(Chapter 2, Section 2.4.4; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2))** and the forest services are working with the pattern observed at the beginning of the 21st century **(Chapter 4, Box 4.3).** While some climate hazards become more frequent **(Chapter**

	3, Section 3.3), timely adaptation measures help reduce the associated risks for most, although poor and disadvantaged groups continue to experience high climate risks to their livelihoods and wellbeing **(Chapter 5, Section 5.3.1; Cross-Chapter Box 12 in chapter 5; Chapter 3, Boxes 3.4 and 3.5; Cross-Chapter Box 6 in Chapter 3)**. Summer sea ice has not completely disappeared from the Arctic (**3.4.4.7**) and coral reefs having been driven to a low level (10-30% of levels in 2018) have partially recovered after extensive dieback by 2100 **(Chapter 3, Section 3.4.4.10 and Box 3.4)**. The Earth system, while warmer, is still recognizable compared to the 2000s and no major tipping points are reached **(Chapter 3, Section 3.5.2.5)**. Crop yields remain relatively stable **(Chapter 3, Section 3.4)**. Aggregate economic damage of climate change impacts is relatively small, although there are some local losses associated with extreme weather events **(Chapter 3, Section 3.5; Chapter 4)**. Human well-being remains overall similar to that in 2020 (**Chapter 5, Section 5.2.2**).
Scenario 2 [one possible storyline among mid-case scenarios]: **Mitigation: Delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, with no efforts to minimize the land and water footprints of bioenergy.** **Internal climate variability: First, 10% worst-case outcome (2020s), then normal internal climate variability**	**The international community continues to largely support the Paris Agreement and agrees in 2020 on reduction targets for CO_2 emissions and time frames for net-zero emissions. However, these targets are not ambitious enough to reach stabilization at 2°C warming, let alone 1.5°C.** **In the 2020s, internal climate variability leads to higher warming than projected, in a reverse development to what happened in the so-called "hiatus" period of the 2000s.** Temperatures are regularly above 1.5°C warming although radiative forcing is consistent with a warming of 1.2°C or 1.3°C. Deadly heatwaves in major cities (Chicago, Kolkata, Beijing, Karachi, São Paulo), droughts in Southern Europe, South Africa and the Western Sahel, and major flooding in Asia, all intensified by the global and regional warming **(Chapter 3, Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.4.8; Chapter 4, Cross-Chapter Box 11 in Chapter 4)**, lead to increasing levels of public unrest and political destabilization (**Chapter 5, Section 5.2.1**). An emergency global summit in 2025 moves to much more ambitious climate targets. Costs for rapidly phasing out fossil fuel use and infrastructure, while rapidly expanding renewables to reduce emissions, are much higher than in Scenario 1 due to a failure to support economic measures to drive the transition **(Chapter 4)**. Disruptive technologies become crucial to face up to the adaptation measures needed **(Chapter 4, Section 4.4.4)**. Temperature peaks at 2°C by the middle of the century before decreasing again due to intensive implementation of bioenergy plants with carbon capture and storage **(Chapter 2)**, without efforts to minimize the land and water footprint of the bioenergy production **(Cross-Chapter Box 7 in Chapter 3)**. Reaching 2°C for several decades eliminates or severely damages key ecosystems such as coral reefs and tropical forests **(Chapter 3, Section 3.4)**. The elimination of coral reef ecosystems and the deterioration of their calcified frameworks, as well as serious losses of coastal ecosystems such as mangrove forests and seagrass beds **(Chapter 3, Box 3.4, Box 3.5, 3.4.4.10, 3.4.5)**, leads to much reduced levels of coastal defence from storms, winds and waves increases the vulnerability and risks facing communities in tropical and sub-tropical regions with consequences for many coastal communities **(Chapter 5, Cross-Chapter Box 12 in Chapter 5)** These impacts are being amplified by steadily rising sea levels **(Chapter 3, Section 3.3.9)** and intensifying storms **(Section 3.4.4.3)**. The intensive area required for the production of bioenergy combined with increasing water stress sets pressures on food prices

	(Cross-Chapter Box 6 in Chapter 3), driving elevated rates of food insecurity, hunger, and poverty **(Chapter 4, Section 4.3.2; Cross-Chaper Box 6 in Chapter 3; Cross-Chapter Box 11 in Chapter 4)**. Crop yields decline significantly in the tropics, leading to prolonged famines in some African countries **(Chapter 3, Section 3.4; Chapter 4 Section 4.3.2)**. Food trumps environment in terms of importance in most countries with the result that natural ecosystems decrease in abundance due to climate change as well as of land-use change **(Cross-Chapter Box 7 in Chapter 3)**. The ability to implement adaptive action to prevent the loss of ecosystems is frustrated under the circumstances and is consequently minimal **(Chapter 3, Section 3.4.4.10)**. Many natural ecosystems, in particular in the Mediterranean, are lost due to the combined effects of climate change and land use change, and extinction rates increase greatly **(Chapter 3, Section 3.4 and Box 3.2)**. By 2100, temperature has decreased but is still higher than 1.5°C, and the yields of some tropical crops are recovering **(Chapter 3, Section 3.4.3)**. Several of the remaining natural ecosystems experience irreversible climate-change related damages whilst others have been lost to land use change, with very rapid increases in the rate of species extinctions **(Chapter 3, Section 3.4; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Cross-Chapter Box 11 in Chapter 4)**. Migration, forced displacement, and loss of identity are extensive in some countries, reversing some achievements in sustainable development and human security **(Chapter 5, Section 5.3.2)**. Aggregate economic impacts of climate change damage are small, but the loss in ecosystem services creates large economic losses **(Chapter 4, Sections 4.3.2 and 4.3.3)**. The health and well-being of people generally decrease from 2020, while the levels of poverty and disadvantage increase very significantly **(Chapter 5, Section 5.2.1)**.
Scenario 3 [one possible storyline among worst-case scenarios]: **Mitigation: Uncoordinated action, major actions late in the 21st century, 3°C warming in 2100.** **Internal climate variability: First unusual (ca. 10%) best-case scenario for one decade, then normal internal climate variability**	**In 2020, despite past pledges, the international support for the Paris Agreement starts to wane. In the years that follow, CO_2 emissions are reduced at local and national level but efforts are limited and not always successful.** **Radiative forcing increases and, due to chance, the most extreme events tend to happen in less populated regions thus not increasing global concerns.** Nonetheless, there are more frequent heatwaves in several cities and less snow in mountain resorts in the Alps, Rockies, and Andes **(Chapter 3, Section 3.3)**. 1.5°C warming is reached by 2030, but no major changes in policies occur. Starting with an intense El Niño-La Niña phase in the 2030s, several catastrophic years occur while global temperature warming starts to approach 2°C. There are major heatwaves on all continents, with deadly consequences in tropical regions and Asian megacities, especially for those ill-equipped for protecting themselves and their communities from the effects of extreme temperatures **(Chapter 3, Sections 3.3.1, 3.3.2 and 3.4.8)**. Droughts occur in regions bordering the Mediterranean Sea, Central North America, the Amazon region and southern Australia, some of which are due to natural variability and others to enhanced greenhouse forcing **(Chapter 3, Section 3.3.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 11 in Chapter 4)**. Intense floodings occur in high-latitude and tropical regions, in particular in Asia, following increases in heavy precipitation events **(Chapter 3, Section 3.3.3)**. Major ecosystems (coral reefs, wetlands, forests) are destroyed over that period **(Chapter 3, Section 3.4)** with massive disruption to local livelihoods **(Chapter 5, Section 5.2.2 and Box 5.3; Cross-Chapter Box 12 in Chapter 5)**. An unprecedented drought leads to large impacts on the Amazon rain forest **(Chapter 3, Sections 3.3.4 and 3.4)**, which is also affected by deforestation **(Chapter 2)**. A hurricane with intense rainfall and

associated with high storm surges **(Chapter 3, Section 3.3.6)** destroys a large part of Miami. A 2-year drought in the Great Plains and a concomitant drought in Eastern Europe and Russia decrease global crop production **(Chapter 3, Section 3.3.4)**, resulting in major increases in food prices and eroding food security. Poverty levels increase to a very large scale and risk and incidence of starvation increase very significantly as food stores dwindle in most countries; human health suffers (**Chapter 3, Section 3.4.6.1; Chapter 4, Sections 4.3.2 and 4.4.3; Chapter 5, Section 5.2.1**).

There are high levels of public unrest and political destabilization due to the increasing climatic pressures, resulting in some countries becoming dysfunctional (**Chapter 4, Sections 4.4.1 and 4.4.2**). The main countries responsible for the CO_2 emissions design rapidly conceived mitigation plans and try to install plants for carbon capture and storage, in some cases without sufficient prior testing (**Chapter 4, Section 4.3.6**). Massive investments in renewable energy often happen too late and are uncoordinated; energy prices soar as a result of the high demand and lack of infrastructure. In some cases, demand cannot be met, leading to further delays. Some countries propose to consider sulphate-aerosol based SRM (**Chapter 4, Section 4.3.8**), however intensive international negotiations on the topic take substantial time and are inconclusive, because of overwhelming concerns about potential impacts to monsoon rainfall and risks in case of termination **(Cross-Chapter Box 10 in Chapter 5)**. Global and regional temperatures continue to strongly increase while mitigation solutions are being developed and implemented.

Global mean warming reaches 3°C by 2100 but is not yet stabilized despite major decreases in yearly CO_2 emissions, as a net-zero CO_2 emissions budget could not yet be achieved and because of the long life-time of CO_2 concentrations **(Chapters 1, 2 and 3)**. The world as it was in 2020 is no longer recognizable, with decreasing life expectancy, reduced outdoor labour productivity, and lower quality of life in many regions because of too frequent heatwaves and other climate extremes (**Chapter 4, Section 4.3.3**). Droughts and water resources stress renders agriculture economically un-viable in some regions **(Chapter 3, Section 3.4; Chapter 4, Section 4.3.2)** and contributes to increases in poverty **(Chapter 5, Section 5.2.1; Cross-Chapter Box 12 in Chapter 5)**. Progress on the sustainable development goals is largely undone and poverty rates reach new highs **(Chapter 5, Section 5.2.3)**. Major conflicts take place **(Chapter 3, Section 3.4.9.6; Chapter 5, Section 5.2.1)**. Almost all ecosystems experience irreversible impacts, species extinction rates are high in all regions, forest fires escalate, and biodiversity strongly decreases, resulting in extensive losses to ecosystem services. These losses exacerbate poverty and reduce quality of life **(Chapter 3, Section 3.4; Chapter 4, Section 4.3.2)**. Life, for many indigenous and rural groups, becomes untenable in their ancestral lands **(Chapter 4, Box 4.3; Chapter 5, Cross-Chapter Box 12 in Chapter 5)**. The retreat of the West Antarctic ice sheet accelerates **(Chapter 3, Sections 3.3 and 3.6)**, leading to more rapid SLR **(Chapter 3, Section 3.3.9; Chapter 4, Section 4.3.2)**. Several small island states give up hope to survive in their place and look to an increasingly fragmented global community for refuge **(Chapter 3, Box 3.5; Chapter 5, Cross-Chapter Box 12 in Chapter 5)**. Aggregate economic damages are substantial owing to the combined effects of climate changes, political instability, and losses of ecosystem services **(Chapter 4, Sections 4.4.1 and 4.4.2; Chapter 3, Box 3.6 and Section 3.5.2.4)**. The general health and well-being of people substantially decreased compared to the conditions in 2020 and continues to worsen over the following decades (**Chapter 5, Section 5.2.3**).

Frequently Asked Questions

FAQ 3.1: What are the impacts of 1.5°C and 2°C of warming?

Summary*: The impacts of climate change are being felt in every inhabited continent and in the oceans. But they are not spread uniformly across the globe, and different parts of the world experience impacts differently. An average warming of 1.5°C across the whole globe raises the risk of heatwaves and heavy rainfall events, amongst many other potential impacts. Limiting warming to 1.5°C rather than 2°C can help reduce these risks. But the impacts the world experiences will depend on the specific greenhouse gas emission 'pathway' taken. The consequences of temporarily overshooting 1.5°C and returning later in the century, for example, could be larger than if temperature stabilizes below 1.5°C. The size and duration of an overshoot will also affect future impacts.*

Human activity has warmed the world by ~1°C since pre-industrial times, and the impacts of this warming are already been felt in many parts of the world. This warming in global temperature is the average of many thousands of temperature measurements taken over the world's land and oceans. But temperatures aren't changing at the same speed everywhere. Warming is greatest on continents and is particularly strong in the Arctic in the cold season and mid-latitude regions in the warm season. This is due to self-amplifying mechanisms which increase resulting warming, for instance due to snow and ice melt reducing the reflectivity of solar radiation at the surface, or soil moisture drying leading to less evaporative cooling in the interior of continents. This means that some parts of the world have already experienced temperatures above 1.5°C above pre-industrial levels.

Extra warming on top of the ~1°C we have seen so far would amplify the risks and associated impacts, with implications for the world and its inhabitants. This would be the case even if the total warming is held at 1.5°C, just half a degree above where we are now, and would be further amplified at 2°C global warming. Reaching 2°C instead of 1.5°C global warming would lead to substantial warming of extreme hot days in all land regions. It would also lead to an increase in heavy rainfall events in some regions, particularly in the high latitudes of the Northern Hemisphere, potentially raising the risk of flooding. In addition, some regions are projected to become drier at 2°C vs 1.5°C global warming, for example the Mediterranean region. The impacts of any additional warming would also include stronger melting of ice sheets and glaciers, as well as increased sea level rise, which would continue long after the stabilization of atmospheric CO_2 concentrations.

Change in climate means and extremes have knock on effects for the societies and ecosystems living on the planet. Climate change is projected to be a poverty multiplier, which means that its impacts make the poor poorer and increase the total number of people living in poverty. The 0.5°C rise in global temperatures that we have experienced in the past 50 years has contributed to shifts in the distribution of plant and animal species, decreasing crop yields and leading to more frequent wildfires. Similar changes can be expected for further rises in global temperature.

Essentially, the lower the rise in global temperature above preindustrial levels, the lower the risks to human societies and natural ecosystems. Put another way, limiting warming to 1.5°C can be understood in terms of 'avoided impacts' compared to higher levels of warming. Many of the impacts of climate change assessed in

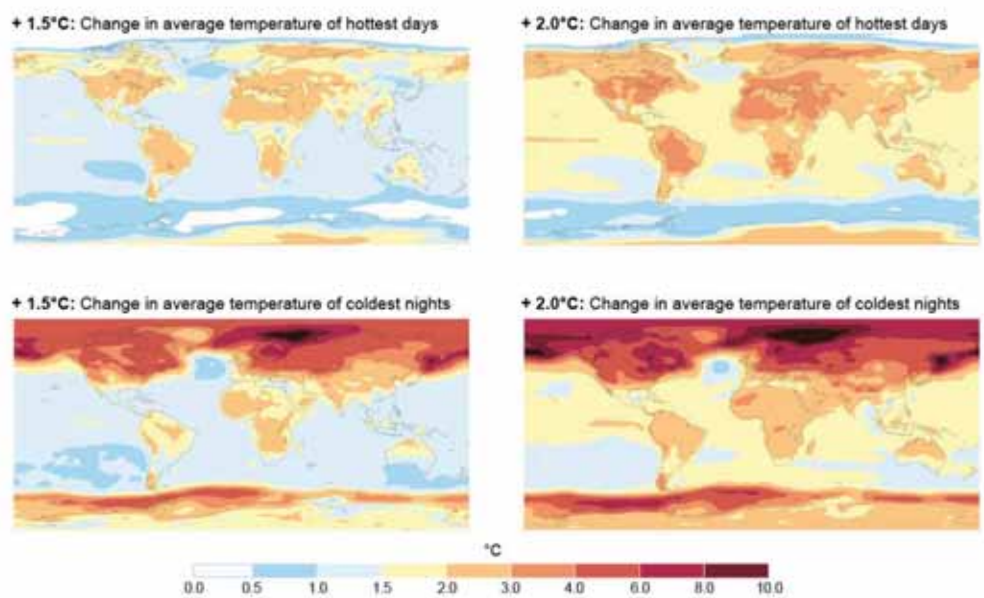
this report have lower associated risks at 1.5°C compared to 2°C.
Thermal expansion of the oceans, resulting from the delayed ocean mixing, means sea level will continue to rise even if global temperature is limited to 1.5°C, but this would be lower than in a 2°C world. Ocean acidification, the process by which excess CO_2 is dissolving into oceans and making them more acidic, is expected to be less damaging in a world where CO_2 emissions are reduced and warming is stabilised at 1.5°C compared to 2°C. The prospect for coral reefs in a 1.5°C world of less damaging than that of a 2ºC world, too.

The impacts of climate change that we experience in future will also be affected by factors other than the change in temperature. The consequences of 1.5°C warming will additionally depend on the specific greenhouse gas emissions 'pathway' that is followed and the extent to which adaptation can reduce vulnerability. This IPCC Special Report uses a number of 'pathways' to explore different possibilities for limiting global warming to 1.5°C above preindustrial levels. One type of pathway sees global temperature stabilize at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down later in the century (known as an 'overshoot' pathway).

Such pathways would have different associated impacts, so it is important to distinguish between them for planning adaptation and mitigation strategies. For example, impacts from an overshoot pathway could be larger than impacts from a stabilization pathway. The size and duration of an overshoot would also have consequences for the impacts the world experiences. For example, pathways that overshoot 1.5°C run a greater risk of passing through 'tipping points'. These are thresholds beyond which certain impacts can no longer be avoided, even if temperatures are brought back down later on. An example is the collapse of the Greenland and Antarctic ice sheets on the time scale of centuries and millennia.

FAQ3.1: **Impact of 1.5°C and 2.0°C global warming**

Temperature rise is not uniform across the world. Some regions will experience greater increases in hot days and decreases in cold nights than others



FAQ 3.1, Figure 1: Temperature change is not uniform across the globe. Projected change in average temperature of the annual hottest day (top) and the annual coldest night (bottom) with 1.5°C global warming (left) and 2°C global warming (right) compared to pre-industrial levels.

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Chapter 4: Strengthening and implementing the global response

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Executive Summary

Limiting warming to 1.5°C would require transformative systemic change, integrated with sustainable development. Such change would require the upscaling and acceleration of the implementation of far-reaching, multi-level and cross-sectoral climate mitigation and addressing barriers. Such systemic change would need to be linked to complementary adaptation actions, including transformational adaptation, especially for pathways that temporarily overshoot 1.5°C {Chapter 2, Chapter 3, 4.2.1, 4.4.5, 4.5} (*medium evidence, high agreement*). Current national pledges on mitigation and adaptation are not enough to stay below the Paris Agreement temperature limits and achieve its adaptation goals. While transitions in energy efficiency, carbon intensity of fuels, electrification and land use change are underway in various countries, limiting warming to 1.5°C will require a greater scale and pace of change to transform energy, land, urban and industrial systems globally. {4.3, 4.4, Cross-Chapter Box CB9 in this Chapter}

Although multiple communities around the world are demonstrating the possibility of implementation consistent with 1.5°C pathways {Boxes 4.1-4.10}, very few countries, regions, cities, communities or businesses can currently make such a claim (*high confidence*). To strengthen the global response, almost all countries would need to significantly raise their level of ambition. Implementation of this raised ambition would require enhanced institutional capabilities in all countries, including building the capability to utilise Indigenous and local knowledge (*medium evidence, high agreement*)**.** In developing countries and for poor and vulnerable people, implementing the response would require financial, technological and other forms of support to build capacity, for which additional local, national and international resources would need to be mobilised (*high confidence*). However, public, financial, institutional and innovation capabilities currently fall short of implementing far-reaching measures at scale in all countries *(high confidence)*. Transnational networks that support multi-level climate action are growing, but challenges in their scale-up remain. {4.4.1, 4.4.2, 4.4.4, 4.4.5, Box 4.1, Box 4.2, Box 4.7}

Adaptation needs will be lower in a 1.5°C world compared to a 2°C world *(high confidence)* {Chapter 3; Cross-Chapter Box CB11 in this Chapter}. Learning from current adaptation practices and strengthening them through adaptive governance {4.4.1}, lifestyle and behavioural change {4.4.3} and innovative financing mechanisms {4.4.5} can help their mainstreaming within sustainable development practices. Preventing maladaptation, drawing on bottom-up approaches {Box 4.6} and using Indigenous knowledge {Box 4.3} would effectively engage and protect vulnerable people and communities. While adaptation finance has increased quantitatively, significant further expansion would be needed to adapt to 1.5°C. Qualitative gaps in the distribution of adaptation finance, readiness to absorb resources and monitoring mechanisms undermine the potential of adaptation finance to reduce impacts. {Chapter 3, 4.4.2, 4.4.5, 4.6}

System transitions

The energy system transition that would be required to limit global warming to 1.5°C is underway in many sectors and regions around the world (*medium evidence, high agreement*). The political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years, while that of nuclear energy and Carbon Dioxide Capture and Storage (CCS) in the electricity sector have not shown similar improvements. {4.3.1}

Electrification, hydrogen, bio-based feedstocks and substitution, and in several cases carbon dioxide capture, utilisation and storage (CCUS), would lead to the deep emissions reductions required in energy-intensive industry to limit warming to 1.5°C. However, those options are limited by institutional, economic and technical constraints, which increase financial risks to many incumbent firms (*medium evidence, high agreement*). Energy efficiency in industry is more economically feasible and an enabler of industrial system transitions but would have to be complemented with Greenhouse Gas (GHG)-neutral processes or Carbon Dioxide Removal (CDR) to make energy-intensive industry consistent with 1.5°C (*high confidence)*. {4.3.1, 4.3.4}

Global and regional land-use and ecosystems transitions and associated changes in behaviour that would be required to limit warming to 1.5°C can enhance future adaptation and land-based agricultural and forestry mitigation potential. Such transitions could, however, carry consequences for livelihoods that depend on agriculture and natural resources {4.3.2, Cross-Chapter Box CB6 in chapter 3}. Alterations of agriculture and forest systems to achieve mitigation goals could affect current ecosystems and their services and potentially threaten food, water and livelihood security. While this could limit the social and environmental feasibility of land-based mitigation options, careful design and implementation could enhance their acceptability and support sustainable development objectives (*medium evidence, medium agreement*). {4.3.2, 4.5.3}

Changing agricultural practices can be an effective climate adaptation strategy. A diversity of adaptation options exists, including mixed crop-livestock production systems which can be a cost-effective adaptation strategy in many global agriculture systems (*robust evidence, medium agreement)*. Improving irrigation efficiency could effectively deal with changing global water endowments, especially if achieved via farmers adopting new behaviour and water-efficient practices rather than through large-scale infrastructure (*medium evidence, medium agreement*). Well-designed adaptation processes such as community-based adaptation can be effective depending upon context and levels of vulnerability. {4.3.2, 4.5.3}

Improving the efficiency of food production and closing yield gaps have the potential to reduce emissions from agriculture, reduce pressure on land and enhance food security and future mitigation potential (*high confidence*). Improving productivity of existing agricultural systems generally reduces the emissions intensity of food production and offers strong synergies with rural development, poverty reduction and food security objectives, but options to reduce absolute emissions are limited unless paired with demand-side measures. Technological innovation including biotechnology, with adequate safeguards, could contribute to resolving current feasibility constraints and expand the future mitigation potential of agriculture. {4.3.2, 4.4.4}

Dietary choices towards foods with lower emissions and requirements for land, along with reduced food loss and waste, could reduce emissions and increase adaptation options (*high confidence*). Decreasing food loss and waste and behavioural change around diets could lead to effective mitigation and adaptation options (*high confidence*) by reducing both emissions and pressure on land, with significant co-benefits for food security, human health and sustainable development {4.3.2, 4.4.5, 4.5.2, 4.5.3, 5.4.2}, but evidence of successful policies to modify dietary choices remains limited.

Mitigation and Adaptation Options and other Measures

A mix of mitigation and adaptation options implemented in a participatory and integrated manner can enable rapid, systemic transitions in urban and rural areas that are necessary elements of an accelerated transition to 1.5°C worlds. Such options and changes are most effective when aligned with economic and sustainable development, and when local and regional governments are supported by national governments {4.3.3, 4.4.1, 4.4.3}, Various mitigation options are expanding rapidly across many geographies. Although many have development synergies, not all income groups have so far benefited from them. Electrification, end-use energy efficiency and increased share of renewables, amongst other options, are lowering energy use and decarbonising energy supply in the built environment, especially in buildings. Other rapid changes needed in urban environments include demotorisation and decarbonisation of transport, including the expansion of electric vehicles, and greater use of energy-efficient appliances (*medium evidence, high agreement*). Technological and social innovations can contribute to limiting warming to 1.5ºC, e.g. by enabling the use of smart grids, energy storage technologies and general-purpose technologies, such as Information and Communication Technology (ICT) that can be deployed to help reduce emissions. Feasible adaptation options include green infrastructure, resilient water and urban ecosystem services, urban and peri-urban agriculture, and adapting buildings and land use through regulation and planning (*medium evidence, medium to high agreement*). {4.3.3}

Synergies can be achieved across systemic transitions through several overarching adaptation options in rural and urban areas. Investments in health, social security and risk sharing and spreading are cost-effective adaptation measures with high potential for scaling-up (*medium evidence, medium to high agreement*). Disaster risk management and education-based adaptation have lower prospects of scalability and cost-effectiveness (*medium evidence, high agreement*) but are critical for building adaptive capacity. {4.3.5, 4.5.3}

Converging adaptation and mitigation options can lead to synergies and potentially increase cost effectiveness, but multiple trade-offs can limit the speed of and potential for scaling up. Many examples of synergies and trade-offs exist in all sectors and system transitions. For instance, sustainable water management (*high evidence, medium agreement*) and investment in green infrastructure (*medium evidence, high agreement*) to deliver sustainable water and environmental services and to support urban agriculture are less cost-effective but can help build climate resilience. Achieving the governance, finance and social support required to enable these synergies and to avoid trade-offs is often challenging, especially when addressing multiple objectives, and appropriate sequencing and timing of interventions. {4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

Though CO_2 dominates long-term warming, the reduction of warming Short-Lived Climate Forcers (SLCFs), such as methane and black carbon, can in the short term contribute significantly to limiting warming to 1.5°C. Reductions of black carbon and methane would have substantial co-benefits (*high confidence)*, including improved health due to reduced air pollution. This, in turn, enhances the institutional and socio-cultural feasibility of such actions. Reductions of several warming SLCFs are constrained by economic and social feasibility *(low evidence, high agreement)*. As they are often co-emitted with CO_2, achieving the energy, land and urban transitions necessary to limit warming to 1.5°C would see emissions of warming SLCFs greatly reduced. {2.3.3.2, 4.3.6}

Most CDR options face multiple feasibility constraints, that differ between options, limiting the potential for any single option to sustainably achieve the large-scale deployment in 1.5°C-consistent pathways in Chapter 2 (*high confidence*). Those 1.5°C pathways typically rely on Bioenergy with Carbon Capture and Storage (BECCS), Afforestation and Reforestation (AR), or both, to neutralise emissions that are expensive to avoid, or to draw down CO_2 emissions in excess of the carbon budget {Chapter 2}. Though BECCS and AR may be technically and geophysically feasible, they face partially overlapping yet different constraints related to land use. The land footprint per tonne CO_2 removed is higher for AR than for BECCS, but in the light of low current deployment, the speed and scales required for limiting warming to 1.5°C pose a considerable implementation challenge, even if the issues of public acceptance and missing economic incentives were to be resolved (*high agreement, medium evidence*). The large potentials of afforestation and their co-benefits if implemented appropriately (e.g. on biodiversity, soil quality) will diminish over time, as forests saturate (*high confidence*). The energy requirements and economic costs of Direct Air Carbon Capture and Storage (DACCS) and enhanced weathering remain high (*medium evidence, medium agreement*). At the local scale, soil carbon sequestration has co-benefits with agriculture and is cost-effective even without climate policy *(high confidence)*. Its potential global feasibility and cost effectiveness appears to be more limited. {4.3.7}

Uncertainties surrounding Solar Radiation Modification (SRM) measures constrain their potential deployment. These uncertainties include: technological immaturity; limited physical understanding about their effectiveness to limit global warming; and a weak capacity to govern, legitimise, and scale such measures. Some recent model-based analysis suggests SRM would be effective but that it is too early to evaluate its feasibility. Even in the uncertain case that the most adverse side-effects of SRM can be avoided, public resistance, ethical concerns and potential impacts on sustainable development could render SRM economically, socially and institutionally undesirable (*low agreement, medium evidence*). {4.3.8, Cross-Chapter Box CB10 in this Chapter}

Enabling Rapid and Far-reaching Change

The speed and scale of transitions and of technological change required to limit warming to 1.5°C has been observed in the past within specific sectors and technologies {4.2.2.1}. But the geographical and economic scales at which the required rates of change in the energy, land, urban, infrastructure and industrial systems would need to take place, are larger and have no documented historic precedent (*limited evidence, medium agreement*). To reduce inequality and alleviate poverty, such transformations would require more planning and stronger institutions (including inclusive markets) than observed in the past, as well as stronger coordination and disruptive innovation across actors and scales of governance. {4.3, 4.4}

Governance consistent with limiting warming to 1.5°C and the political economy of adaptation and mitigation can enable and accelerate systems transitions, behavioural change, innovation and technology deployment (*medium evidence, medium agreement*). For 1.5°C-consistent actions, an effective governance framework would include: accountable multi-level governance that includes non-state actors such as industry, civil society and scientific institutions; coordinated sectoral and cross-sectoral policies that enable collaborative multi-stakeholder partnerships; strengthened global-to-local financial architecture that enables greater access to finance and technology; and addresses climate-related trade barriers; improved climate education and greater public awareness; arrangements to enable accelerated behaviour change; strengthened climate monitoring and evaluation systems; and reciprocal international agreements that are sensitive to equity and the Sustainable Development Goals (SDGs). System transitions can be enabled by enhancing the capacities of public, private and financial institutions to accelerate climate change policy planning and implementation, along with accelerated technological innovation, deployment and upkeep. {4.4.1, 4.4.2, 4.4.3, 4.4.4}

Behaviour change and demand-side management can significantly reduce emissions, substantially limiting the reliance on CDR to limit warming to 1.5°C {Chapter 2, 4.4.3}. Political and financial stakeholders may find climate actions more cost-effective and socially acceptable, if multiple factors affecting behaviour are considered, including aligning them with people's core values (*medium evidence, high agreement*). Behaviour- and lifestyle-related measures and demand-side management have already led to emission reductions around the world and can enable significant future reductions *(high confidence)*. Social innovation through bottom-up initiatives can result in greater participation in the governance of systems transitions and increase support for technologies, practices and policies that are part of the global response to 1.5°C. {Chapter 2, 4.4.1, 4.4.3, Figure 4.3}

This rapid and far-reaching response required to keep warming below 1.5°C and enhance the adaptive capacity to climate risks needs large investments in low-emission infrastructure and buildings that are currently underinvested, along with a redirection of financial flows towards low-emission investments *(robust evidence, high agreement).* An estimated annual incremental investment of 1% to 1.5% of global Gross Fixed Capital Formation (GFCF) for the energy sector is indicated; and 1.7% to 2.5% of global GFCF for other development infrastructure that could also address SDG implementation. Though quality policy design and effective implementation may enhance efficiency, they cannot substitute for these investments. {2.5.2, 4.2.1}

Enabling this investment requires the mobilisation and better integration of a range of policy instruments that include: the reduction of socially inefficient fossil fuel subsidy regimes and innovative price and non-price national and international policy instruments and would need to be complemented by de-risking financial instruments and the emergence of long-term low-emission assets. These instruments would aim to reduce the demand for carbon-intensive services and shift market preferences away from fossil fuel-based technology. Evidence and theory suggest that carbon pricing alone, in the absence of sufficient transfers to compensate their unintended distributional cross-sector, cross-nation effects, cannot reach the levels needed to trigger system transitions *(robust evidence, medium agreement)*. But, embedded in consistent policy-packages, they can help mobilise incremental resources and provide flexible mechanisms that help reduce the social and economic costs of the triggering phase of the transition *(robust evidence, medium agreement)*. {4.4.3, 4.4.4, 4.4.5}

Increasing evidence suggests that a climate-sensitive realignment of savings and expenditure towards low-emission, climate-resilient infrastructure and services requires an evolution of global and national financial systems. Estimates suggest that, in addition to climate-friendly allocation of public investments, a potential redirection of 5% to 10% of the annual capital revenues[1] is necessary {4.4.5, Table 1 in Box 4.8}. This could be facilitated by a change of incentives for private day-to-day expenditure and the redirection of savings from speculative and precautionary investments, towards long-term productive low-emission assets and services. This implies the mobilisation of institutional investors and mainstreaming of climate finance within financial and banking system regulation. Access by developing countries to low-risk and low-interest finance through multilateral and national development banks would have to be facilitated *(medium evidence, high agreement)*. New forms of public-private partnerships may be needed with multilateral, sovereign and sub-sovereign guarantees to de-risk climate-friendly investments, support new business models for small-scale enterprises and help households with limited access to capital. Ultimately, the aim is to promote a portfolio shift towards long-term low-emission assets, that would help redirect capital away from potential stranded assets *(medium evidence, medium agreement).* {4.4.5}

Knowledge Gaps

Knowledge gaps around implementing and strengthening the global response to climate change would need to be urgently resolved if the transition to 1.5°C worlds is to become reality. Remaining questions include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (including Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC)), reciprocity and partnership? To what extent limit warming to 1.5°C needs a harmonisation of macro-financial and fiscal policies, that could include financial regulators such as central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives? {4.1, 4.4.1, 4.3.7, 4.4.5, 4.6}

[1] FOOTNOTE: Annual capital revenues are the paid interests plus the increase of the asset value.

4.1 Accelerating the Global Response to Climate Change

This chapter discusses how the global economy and socio-technical and socio-ecological systems can transition to 1.5°C-consistent pathways and adapt to warming of 1.5°C. In the context of systemic transitions, the chapter assesses adaptation and mitigation options, including Carbon Dioxide Removal (CDR), and potential Solar Radiation Modification (SRM) remediative measures (Section 4.3), as well as the enabling conditions that would facilitate implementing the rapid and far-reaching global response (Section 4.4), and render the options more or less feasible (Section 4.5).

The impacts of 1.5°C warmer worlds, while less than in a 2°C warmer world, would require complementary adaptation and development action, typically at local and national scale. From a mitigation perspective, 1.5°C-consistent pathways require immediate action on a greater and global scale so as to achieve net-zero emissions by mid-century, or earlier (Chapter 2). This chapter and Chapter 5 highlight the potential that combined mitigation, development and poverty reduction offer for accelerated decarbonisation.

The global context is an increasingly interconnected world, with the human population growing from the current 7.6 billion to over 9 billion by mid-century (UN, 2017). There has been a consistent growth of global economic output, wealth and trade with a significant reduction in extreme poverty. These trends could continue for the next few decades (Burt et al., 2014), potentially supported by new and disruptive information and communication, and nano- and bio-technologies. They however co-exist with rising inequality (Piketty, 2014), exclusion and social stratification, and regions locked in poverty traps (Deaton, 2013) that could fuel social and political tensions.

The aftermath of the 2008 financial crisis generated a challenging environment on which leading economists have issued repeated alerts about the 'discontents of globalisation' (Stiglitz, 2002), 'depression economics' (Krugman, 2009), an excessive reliance of export-led development strategies (Rajan, 2011), and risks of 'secular stagnation' due to the 'saving glut' that slows down the flow of global savings towards productive 1.5°C-consistent investments (Summers, 2016). Each of these impacts the implementation of both 1.5°C-consistent pathways and sustainable development (Chapter 5).

The range of mitigation and adaptation actions that can be deployed in the short run are well-known: for example, low-emission technologies, new infrastructure, energy efficiency measures in buildings, industry and transport; transformation of fiscal structures; reallocation of investments and human resources towards low-emission assets; sustainable land and water management, ecosystem restoration, enhancement of adaptive capacities to climate risks and impacts, disaster risk management; research and development; and mobilisation of new, traditional and Indigenous knowledge.

The convergence of short-term development co-benefits of mitigation and adaptation to address 'everyday development failures' (e.g., institutions, market structures and political processes) (Hallegatte et al., 2016; Pelling et al., 2018) could enhance the adaptive capacity of key systems at risk (e.g., water, energy, food, biodiversity, urban, regional and coastal systems) to 1.5°C climate impact (Chapter 3). The issue is whether aligning 1.5°C-consistent pathways with the Sustainable Development Goals (SDGs) will secure support for accelerated change and a new growth cycle (Stern, 2013, 2015). It is difficult to imagine how a 1.5°C world would be attained unless the SDG on cities and sustainable urbanisation is attained in developing countries (Revi, 2016), or without reforms in the global financial intermediation system.

Unless affordable and environmentally and socially acceptable CDR become feasible and available at scale well before 2050, 1.5°C-consistent pathways will be difficult to realise, especially in overshoot scenarios. The social costs and benefits of 1.5°C-consistent pathways depend on the depth and timing of policy responses and their alignment with short term and long-term development objectives, through policy packages that bring together a diversity of policy instruments, including public investment (Campiglio 2016; Winkler and Dubash 2015; Grubb et al. 2014).

Whatever its potential long-term benefits, a transition to a 1.5°C world may suffer from a lack of broad political and public support, if it exacerbates existing short-term economic and social tensions, including unemployment, poverty, inequality, financial tensions, competitiveness issues and the loss of economic value of carbon-intensive assets (Mercure et al., 2018). The challenge is therefore how to strengthen climate policies without inducing economic collapse or hardship, and to make them contribute to reducing some of the 'fault lines' of the world economy (Rajan, 2011).

This chapter reviews literature addressing the alignment of climate with other public policies (e.g., fiscal, trade, industrial, monetary, urban planning, infrastructure, innovation) and with a greater access to basic needs and services, defined by the SDGs. It also reviews how de-risking low-emission investments and the evolution of the financial intermediation system can help reduce the 'savings glut' (Arezki et al., 2016) and the gap between cash balances and long-term assets (Aglietta et al., 2015b) to support more sustainable and inclusive growth.

As the transitions associated with 1.5°C-consistent pathways require accelerated and coordinated action, in multiple systems across all world regions, they are inherently exposed to risks of freeriding and moral hazards. A key governance challenge is how the convergence of voluntary domestic policies can be organised via aligned global, national and sub-national governance, based on reciprocity (Ostrom and Walker, 2005) and partnership (UN, 2016), and how different actors and processes in climate governance can reinforce each other to enable this (Gupta, 2014; Andonova et al., 2017). The emergence of polycentric sources of climate action and transnational and subnational networks that link these efforts (Abbott et al., 2012) offer the opportunity to experiment and learn from different approaches, thereby accelerating approaches led by national governments (Cole, 2015; Jordan et al., 2015).

Section 4.2 of this chapter outlines existing rates of change and attributes of accelerated change. Section 4.3 identifies global systems, and their components, that offer options for this change. Section 4.4 documents the enabling conditions that influence the feasibility of those options, including economic, financial and policy instruments that could trigger the transition to 1.5°C-consistent pathways. Section 4.5 assesses mitigation and adaptation options for feasibility, strategies for implementation and synergies and trade-offs between mitigation and adaptation.

4.2 Pathways Compatible with 1.5ºC: Starting Points for Strengthening Implementation

4.2.1 Implications for Implementation of 1.5ºC-consistent Pathways

The 1.5°C-consistent pathways assessed in Chapter 2 form the basis for the feasibility assessment in section 4.3. A wide range of 1.5°C-consistent pathways from both Integrated Assessment Modelling (IAM), supplemented by other literature, are assessed by Chapter 2 (Sections 2.1, 2.3, 2.4, and 2.5). The most common feature shared by these pathways is their requirement for faster and more radical changes compared to 2°C and higher warming pathways.

A variety of 1.5°C-consistent technological options and policy targets is identified in the assessed modelling literature (Sections 2.3, 2.4, 2.5). These technology and policy options include energy demand reduction, greater penetration of low-emission and carbon-free technologies as well as electrification of transport and industry, and reduction of land-use change. Both the detailed integrated modelling pathway literature and a number of broader sectoral and bottom-up studies provide examples of how these sectoral technological and policy characteristics can be broken down sectorally for 1.5°C-consistent pathways (see Table 4.1).

Both the integrated pathway literature and the sectoral studies agree on the need for rapid transitions in the production and use of energy across various sectors, to be consistent with limiting global warming to 1.5°C. The pace of these transitions are particularly significant for the supply mix and electrification, with sectoral studies projecting a higher pace of change compared to IAMs (Table 4.1). These trends and transformation patterns create opportunities and challenges for both mitigation and adaptation (Sections 4.2.1.1 and 4.2.1.2), and have significant implications for the assessment of feasibility and enablers, including governance, institutions, and policy instruments addressed in Sections 4.3 and 4.4.

Table 4.1: Sectoral indicators of the pace of transformation in 1.5°C-consistent pathways, based on selected integrated pathways assessed in Chapter 2 (from the scenario database) and sectoral studies reviewed in Chapter 2 that assess mitigation transitions consistent with limiting warming to 1.5°C. Values for '1.5C low OS' and '1.5C high OS' indicate the median and the interquartile ranges for 1.5°C scenarios distinguishing high and low overshoot. S1, S2, S5 and LED represent the four illustrative pathway archetypes selected for this assessment (see Section 2.1 and Supplementary Material 4.A for detailed description).

		Energy		Buildings	Transport		Industry
		Share of renewable in primary energy [%]	Share of renewable in electricity [%]	Change in energy demand for buildings (2010 baseline) [%]	Share of low carbon fuels (electricity, hydrogen and biofuel) in transport [%]	Share of electricity in transport [%]	Industrial emissions reductions (based on current level) [%]
IAM Pathways 2030	1.5C low OS	29 (35; 25)	53 (59; 44)	-3 (5; -8)	10 (15; 8)	5 (7; 3)	40 (50; 30)
	1.5C high OS	24 (27; 20)	43 (54; 37)	-17 (-12; -20)	7 (8; 6)	3 (5; 3)	18 (28; -13)
	S1	29	58	-8	NA	4	49
	S2	29	48	-14	5	4	19
	S5	14	25	NA	3	1	NA
	LED	37	60	30	NA	21	42
Sectorial studies 2030	Löffler et al. (2017)	50	78				
	Rockström et al. (2017)	20					
	Kuramochi et al. (2017)						20
	IEA (2017)	20	47	7	16	6	14
	WBCSD (2017)			-11			
IAM Pathways 2050	1.5C low OS	58 (67; 50)	76 (85; 69)	-19 (2; -37)	53 (65; 34)	23 (30; 17)	79 (89; 71)
	1.5C high OS	62 (68; 47)	82 (88; 64)	-37 (-13; -51)	38 (44; 27)	18 (23; 14)	68 (81; 54)
	S1	58	81	-21	NA	34	74
	S2	53	63	-25	26	23	73
	S5	67	70	NA	53	10	NA
	LED	73	77	45	NA	59	91
Sectorial studies 2050	Löffler et al. (2017)	100	100		98		
	Rockström et al. (2017)		100				
	Figueres et al. (2017)						50
	Kuramochi et al. (2017)		100				
	IEA (2017)	29	74	11	59	31	20
	WBCSD (2017)						

4.2.1.1 Challenges and Opportunities for Mitigation Along the Reviewed Pathways

4.2.1.1.1 Greater scale, speed and change in investment patterns

There is agreement in the literature reviewed by Chapter 2 that staying below 1.5°C would entail significantly greater transformation in terms of energy systems, lifestyles and investments patterns compared to 2°C-consistent pathways. Yet there is *limited evidence* and *low agreement* regarding the magnitudes and costs of the investments (Sections 2.5.1, 2.5.2 and 4.4.5). Based on the IAM literature reviewed in Chapter 2, climate policies in line with limiting warming to 1.5°C would require a marked upscaling of supply-side energy system investments between now and mid-century, reaching levels of between 1.6–3.8 trillion USD

yr^{-1} globally with an average of about 3.5 trillion USD yr^{-1} over 2016-2050 (see Figure 2.27). This can be compared to an average of about 3.0 trillion USD yr^{-1} over the same period for 2°C-consistent pathways (also in Figure 2.27).

Not only the level of investment but also the type and speed of sectoral transformation would be impacted by the transitions associated with 1.5°C-consistent pathways. IAM literature projects that investments in low-emission energy overtake fossil-fuel investments globally by 2025 in 1.5ºC-consistent pathways (Section 2.5.2). The projected low-emission investments in electricity generation allocations over the period 2016–2050 are: solar (0.09–1.0 trillion USD yr^{-1}), wind (0.1–0.35 trillion USD yr^{-1}), nuclear (0.1–0.25 trillion USD yr^{-1}), and transmission, distribution, and storage (0.3–1.3 trillion USD yr^{-1}). In contrast, investments in fossil-fuel extraction and unabated fossil electricity generation along a 1.5°C-consistent pathway are projected to drop by 0.3-0.85 trillion USD yr^{-1} over the period 2016–2050, with investments in unabated coal generation projected to halt by 2030 in most 1.5°C-consistent pathways (Section 2.5.2). Estimates of investments in other infrastructure are currently unavailable, but they could be considerably larger in volume than solely those in the energy sector (Section 4.4.5).

4.2.1.1.2 Greater policy design and decision-making implications

1.5°C-consistent pathways raise multiple challenges for effective policy design and responses to address the scale, speed, and pace of mitigation technology, finance and capacity building needs. They also need to deal with their distributional implications, while addressing adaptation to residual climate impacts (see Chapter 5). The available literature indicates that 1.5°C-consistent pathways would require robust, stringent and urgent transformative policy interventions targeting the decarbonisation of energy supply, electrification, fuel switching, energy efficiency, land-use change, and lifestyles (Sections 2.5, 4.4.2, 4.4.3). Examples of effective approaches to integrate mitigation with adaptation in the context of sustainable development and to deal with distributional implications proposed in the literature include the utilisation of dynamic adaptive policy pathways (Haasnoot et al., 2013; Mathy et al., 2016) and transdisciplinary knowledge systems (Bendito and Barrios, 2016).

Yet, even with good policy design and effective implementation, 1.5°C-consistent pathways would incur higher costs. Projections of the magnitudes of global economic costs associated with 1.5°C-consistent pathways and their sectoral and regional distributions from the currently assessed literature are scant, yet suggestive. For example, IAM simulations assessed in Chapter 2 project (with a probability greater than 50%) that marginal abatement costs, typically represented in IAMs through a carbon price, would increase by about threefold by 2050 under a 1.5°C-consistent pathway compared to a 2°C-consistent pathway (Section 2.5.2, Figure 2.26). Managing these costs and distributional effects would require an approach that takes account of unintended cross-sector, cross-nation, and cross-policy trade-offs during the transition (Droste et al., 2016; Stiglitz et al., 2017; Pollitt, 2018; Sands, 2018; Siegmeier et al., 2018).

4.2.1.1.3 Greater sustainable development implications

Few studies address the relations between the Shared Socioeconomic Pathways (SSPs) and the Sustainable Developments Goals (SDGs) (O'Neill et al., 2015; Riahi et al., 2017). Nonetheless, literature on potential synergies and trade-offs between 1.5°C-consistent mitigation pathways and sustainable development dimensions is emerging (Sections 2.5.3, 5.4). Areas of potential trade-offs include reduction in final energy demand in relation to SDG 7 (the universal clean energy access goal) and increase of biomass production in relation to land use, water resources, food production, biodiversity and air quality (Sections 2.4.3, 2.5.3). Strengthening the institutional and policy responses to deal with these challenges are discussed in Section 4.4 together with the linkage between disruptive changes in the energy sector and structural changes in other infrastructure (transport, building, water and telecommunication) sectors. A more in-depth assessment of the complexity and interfaces between 1.5°C-consistent pathways and sustainable development is presented in Chapter 5.

4.2.1.2 Implications for Adaptation Along the Reviewed Pathways

Climate variability and uncertainties in the underlying assumptions in Chapter 2's IAMs as well as in model comparisons complicate discerning the implications for climate impacts, adaptation options and avoided adaptation investments at the global level of 2°C compared to 1.5°C warming (James et al., 2017; Mitchell et al., 2017).

Incremental warming from 1.5°C to 2°C would lead to significant increases in temperature and precipitation extremes in many regions (Section 3.3.2, 3.3.3). Those projected changes in climate extremes under both warming levels, however, depend on the emissions pathways, as they have different greenhouse gas (GHG)/aerosol forcing ratios. Impacts are sector-, system- and region-specific, as described in Chapter 3. For example, precipitation-related impacts reveal distinct regional differences (Sections 3.3.3, 3.3.4, 3.3.5, 3.4.2). Similarly, regional reduction in water availability and the lengthening of regional dry spells have negative implications for agricultural yields depending on crop types and world regions (see for example Sections 3.3.4, 3.4.2, 3.4.6).

Adaptation helps reduce impacts and risks. However, adaptation has limits. Not all systems can adapt, and not all impacts can be reversed (Cross-Chapter Box 12 in Chapter 5). For example, tropical coral reefs are projected to be at risk of severe degradation due to temperature-induced bleaching (Box 3.4).

4.2.2 System Transitions and Rates of Change

Society-wide transformation involves socio-technical transitions and social-ecological resilience (Gillard et al., 2016). Transitional adaptation pathways would need to respond to low-emission energy and economic systems, and the socio-technical transitions for mitigation involve removing barriers in social and institutional processes that could also benefit adaptation (Pant et al., 2015; Geels et al., 2017; Ickowitz et al., 2017). In this chapter, transformative change is framed in mitigation around socio-technical transitions, and in adaptation around socio-ecological transitions. In both instances, emphasis is placed on the enabling role of institutions (including markets, and formal and informal regulation). 1.5°C-consistent pathways and adaptation needs associated with warming of 1.5°C imply both incremental and rapid, disruptive and transformative changes.

4.2.2.1 Mitigation: Historical Rates of Change and State of Decoupling

Realising 1.5°C-consistent pathways would require rapid and systemic changes on unprecedented scales (see Chapter 2 and Section 4.2.1). This section examines whether the needed rates of change have historical precedents and are underway.

Some studies conduct a de-facto validation of IAM projections. For CO_2 emission intensity over 1990–2010, this resulted in the IAMs projecting declining emission intensities while actual observations showed an increase. For individual technologies (in particular solar energy), IAM projections have been conservative regarding deployment rates and cost reductions (Creutzig et al., 2017), suggesting that IAMs do not always impute actual rates of technological change resulting from influence of shocks, broader changes and mutually reinforcing factors in society and politics (Geels and Schot, 2007; Daron et al., 2015; Sovacool, 2016; Battiston et al., 2017).

Other studies extrapolate historical trends into the future (Höök et al., 2011; Fouquet, 2016), or contrast the rates of change associated with specific temperature limits in IAMs (such as those in Chapter 2) with historical trends to investigate plausibility of emission pathways and associated temperature limits (Wilson et al., 2013; Gambhir et al., 2017; Napp et al., 2017). When metrics are normalised to Gross Domestic Product (GDP; as opposed to other normalisation metrics such as primary energy), low-emission technology deployment rates used by IAMs over the course of the coming century are shown to be broadly consistent with past trends, but rates of change in emission intensity are typically overestimated (Wilson et al., 2013;

Loftus et al., 2014; van Sluisveld et al., 2015). This bias is consistent with the findings from the 'validation' studies cited above, suggesting that IAMs may under-report the potential for supply-side technological change assumed in 1.5°-consistent pathways, but may be more optimistic about the systemic ability to realise incremental changes in reduction of emission intensity as a consequence of favourable energy efficiency payback times (Wilson et al., 2013). This finding suggests that barriers and enablers other than costs and climate limits play a role in technological change, as also found in the innovation literature (Hekkert et al., 2007; Bergek et al., 2008; Geels et al., 2016b).

One barrier to a greater rate of change in energy systems is that economic growth in the past has been coupled to the use of fossil fuels. Disruptive innovation and socio-technical changes could enable the decoupling of economic growth from a range of environmental drivers, including the consumption of fossil fuels, as represented by 1.5°C-consistent pathways (UNEP, 2014; Newman, 2017). This may be relative decoupling due to rebound effects that see financial savings generated by renewable energy used in the consumption of new products and services (Jackson and Senker, 2011; Gillingham et al., 2013), but in 2015 and 2016 total global GHG emissions have decoupled absolutely from economic growth (IEA, 2017g; Peters et al., 2017). A longer data trend would be needed before stable decoupling can be established. The observed decoupling in 2015 and 2016 was driven by absolute declines in both coal and oil use since the early 2000s in Europe, in the past seven years in the United States and Australia, and more recently in China (Newman, 2017). In 2017, decoupling in China reversed by 2% due to a drought and subsequent replacement of hydropower with coal-fired power (Tollefson, 2017), but this reversal is expected to be temporary (IEA, 2017c). Oil consumption in China is still rising slowly, but absolute decoupling is ongoing in megacities like Beijing (Gao and Newman, 2018) (see Box 4.9).

4.2.2.2 Transformational Adaptation

In some regions and places, incremental adaptation would not be sufficient to mitigate the impacts of climate change on social-ecological systems (see Chapter 3). Transformational adaptation would then be required (Bahadur and Tanner, 2014; Pant et al., 2015; Gillard, 2016; Gillard et al., 2016; Colloff et al., 2017; Termeer et al., 2017). Transformational adaptation refers to actions aiming at adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices (Dowd et al., 2014; IPCC, 2014a; Few et al., 2017), including approaches that enable new ways of decision-making on adaptation (Colloff et al., 2017). Few studies have assessed the potentially transformative character of adaptation options (Pelling et al., 2015; Rippke et al., 2016; Solecki et al., 2017), especially in the context of warming of 1.5°C.

Transformational adaptation can be adopted at a large scale, can lead to new strategies in a region or resource system, transform places and potentially shifts locations (Kates et al., 2012). Some systems might require transformational adaptation at 1.5°C. Implementing adaptation policies in anticipation of 1.5°C would require transformation and flexible planning of adaptation (sometimes called adaptation pathways) (Rothman et al., 2014; Smucker et al., 2015; Holland, 2017; Gajjar et al., 2018), an understanding of the varied stakeholders involved and their motives, and knowledge of less visible aspects of vulnerability based on social, cultural, political, and economic factors (Holland, 2017). Transformational adaptation would seek deep and long-term societal changes that influence sustainable development (Chung Tiam Fook, 2017; Few et al., 2017).

Adaptation requires multidisciplinary approaches integrating scientific, technological and social dimensions. For example, a framework for transformational adaptation, and the integration of mitigation and adaptation pathways can transform rural indigenous communities to address risks of climate change and other stressors (Thornton and Comberti, 2017). In villages in rural Nepal, transformational adaptation has taken place with villagers changing their agricultural and pastoralist livelihood strategies after years of lost crops due to changing rain patterns and degradation of natural resources (Thornton and Comberti, 2017). Instead, they are now opening stores, hotels, and tea shops. In another case, the arrival of an oil pipeline altered traditional Alaskan communities' livelihoods. With growth of oil production, investments were made for rural development. A later drop in oil production decreased these investments. Alaskan Indigenous populations are also dealing with impacts of climate change, such as sea level rise, which is altering their livelihood sources. Transformational adaptation is taking place by changing the energy matrix to renewable energy, in which indigenous people apply their knowledge to achieve environmental, economic, and social benefits (Thornton and Comberti, 2017).

4.2.2.3 Disruptive Innovation

Demand-driven disruptive innovations that emerge as the product of political and social changes across multiple scales can be transformative (Seba, 2014; Christensen et al., 2015; Green and Newman, 2017a). Such innovations would lead to simultaneous, profound changes in behaviour, economies and societies (Seba, 2014; Christensen et al. 2015), but are difficult to predict in supply-focussed economic models (Geels et al., 2016a; Pindyck, 2017). Rapid socio-technical change has been observed in the solar industry (Creutzig et al. (2017). Similar changes to socio-ecological systems can stimulate adaptation and mitigation options that lead to more climate-resilient systems (Adger et al., 2005; Ostrom, 2009; Gillard et al., 2016) (see the Alaska and Nepal examples in Section 4.2.2.2). The increase in roof-top solar and energy storage technology as well as the increase in passive housing and net zero-emissions buildings are further examples of such disruptions (Green and Newman, 2017b). Both roof-top solar and energy storage have benefitted from countries' economic growth strategy and associated price declines in photovoltaic technologies, particularly in China (Hsu et al., 2017; Shrivastava and Persson, 2018), as well as from new information and communication technologies (Koomey et al., 2013), rising demand for electricity in urban areas, and global concern regarding greenhouse gas emissions (Azeiteiro et al., 2017; Lutz and Muttarak, 2017; Wamsler, 2017).

System co-benefits can create the potential for mutually enforcing and demand-driven climate responses (Jordan et al., 2015; Hallegatte and Mach, 2016; Pelling et al., 2018), and rapid and transformational change (Cole, 2015; Geels et al., 2016b; Hallegatte and Mach, 2016; Peters et al., 2017). Examples of co-benefits include gender equality, agricultural productivity (Nyantakyi-Frimpong and Bezner-Kerr, 2015), reduced indoor air pollution (Satterthwaite and Bartlett, 2017), flood buffering (Colenbrander et al., 2017), livelihood support (Shaw et al., 2014; Ürge-Vorsatz et al., 2014), economic growth (GCEC, 2014; Stiglitz et al., 2017), social progress (Steg et al., 2015; Hallegatte and Mach, 2016) and social justice (Ziervogel et al., 2017; Patterson et al., 2018).

Innovations that disrupt entire systems may leave firms and utilities with stranded assets as the transition can happen very quickly (IPCC, 2014b; Kossoy et al., 2015). This may have consequences for fossil fuels that are rendered 'unburnable' (McGlade and Ekins, 2015) and fossil fuel-fired power and industry assets that would become obsolete (Caldecott, 2017; Farfan and Breyer, 2017). The presence of multiple barriers and enablers operating in a system implies that rapid change, whether the product of many small changes (Sterling et al., 2017; Termeer et al., 2017) or large-scale disruptions, is seldom an insular or discrete process. This finding informs the multi-dimensional nature of feasibility in Cross-Chapter Box 3 in Chapter 1 which is applied in Section 4.5. Climate responses that are aligned with multiple feasibility dimensions and combine adaptation and mitigation interventions with non-climate benefits can accelerate change and reduce risks and costs (Fazey et al., 2018). Also political, social and technological influences on energy transitions, for example, can accelerate them faster than narrow techno-economic analysis suggests is possible (Kern and Rogge, 2016), but could also introduce new constraints and risks (Geels et al., 2016b; Sovacool, 2016; Eyre et al., 2018).

Disruptive innovation and technological change may play a role in mitigation and in adaptation. The next section assesses mitigation and adaption options in energy, land and ecosystem, urban and infrastructure and industrial systems.

4.3 Systemic Changes for 1.5°C-Consistent Pathways

Section 4.2 emphasises the importance of systemic change for 1.5°C-consistent pathways. This section translates this into four main system transitions: energy, land and ecosystem, urban and infrastructure, and industrial system transitions. This section assesses the mitigation, adaptation and carbon dioxide removal options that offer the potential for such change within those systems, based on options identified by Chapter 2 and risks and impacts in Chapter 3.

The section puts more emphasis on those adaptation options (Sections 4.3.1-4.3.5) and mitigation options (Sections 4.3.1-4.3.4, 4.3.6 and 4.3.7) that are 1.5°C-relevant and have developed considerably since AR5. They also form the basis for the mitigation and adaptation feasibility assessments in Section 4.5. Section 4.3.8 discusses solar radiation modification methods.

This section emphasises that no single solution or option can enable a global transition to 1.5°C-consistent pathways or adapting to projected impacts. Rather, accelerating change, much of which is already starting or underway, in multiple global systems, simultaneously and at different scales, could provide the impetus for these system transition. The feasibility of individual options as well as the potential for synergies and reduce trade-offs will vary according to context and the local enabling conditions. These are explored at a high level in Section 4.4. Policy packages that bring together multiple enabling conditions can provide building blocks for a strategy to scale-up implementation and intervention impacts.

4.3.1 Energy System Transitions

This section discusses the feasibility of mitigation and adaptation options related to the energy system transition. As only options relevant to 1.5°C and with significant changes since AR5 are discussed, which means that for options like hydropower and geothermal energy, the chapter refers to AR5 and does not provide a discussion. Socio-technical inertia of energy options for 1.5°C-consistent pathways are increasingly being surmounted as fossil fuels start to be phased out. Supply-side mitigation and adaptation options, energy demand-side options, including energy efficiency in buildings and transportation, are discussed in Section 4.3.3, options around energy use in industry are discussed in Section 4.3.4.

Section 4.5 assesses the feasibility in a systematic manner based on the approach outlined in Cross-Chapter Box 3 in Chapter 1.

4.3.1.1 Renewable Electricity: Solar and Wind

All renewable energy options have seen considerable advances over the years since AR5, but solar energy and both onshore and offshore wind energy have had dramatic growth trajectories. They appear well underway to contribute to 1.5°C-consistent pathways (REN21, 2012; IEA, 2017c; IRENA, 2017b).

The largest growth driver for renewable energy since AR5 has been the dramatic reduction in the cost of solar PV (REN21, 2012). This has made rooftop solar competitive in sunny areas between 45° north and south (Green and Newman, 2017b), though IRENA (2018) suggests it is cost effective in many other places too. Solar Photovoltaics (PV) with batteries have been cost effective in many rural and developing areas (Pueyo and Hanna, 2015; Szabó et al., 2016; Jimenez, 2017), for example 19 million people in Bangladesh now have solar-battery electricity in remote villages and are reporting positive experiences on safety and ease of use (Kabir et al., 2017). Small-scale distributed energy projects are being implemented in developed and developing cities where residential and commercial rooftops offer potential for consumers becoming producers (called prosumers) (ACOLA, 2017; Kotilainen and Saari, 2018). Such prosumers could contribute significantly to electricity generation in sun-rich areas likeCalifornia (Kurdgelashvili et al., 2016) or Sub-Saharan Africa in combination with micro-grids and mini-grids Bertheau et al. (2017). It could also contribute to universal energy access (SDG 7) as shown by (IEA, 2017c).

The feasibility of renewable energy options depends to a large extent on geophysical characteristics of the area where the option is implemented. However, technological advances and policy instruments make renewable energy options increasingly attractive in other areas. For example, solar PV is deployed commercially in areas with low solar insolation, like North-Western Europe (Nyholm et al., 2017). Feasibility also depends on grid adaptations (e.g., storage, see below) as renewables grow (IEA, 2017c). For regions with high energy needs, such as industrial areas (see section 4.3.4), high-voltage DC transmission across long distances would be needed (MacDonald et al., 2016).

Another important factor affecting feasibility is public acceptance, in particular for wind energy and other large-scale renewable facilities (Yenneti and Day, 2016; Rand and Hoen, 2017; Gorayeb et al., 2018) that raise landscape management (Nadaï and Labussière, 2017) and distributional justice (Yenneti and Day, 2016) challenges. Research indicates that financial participation and community engagement can be effective in mitigating resistance (Brunes and Ohlhorst, 2011; Rand and Hoen, 2017) (see Section 4.4.3).

Bottom-up studies estimating the use of renewable energy in the future, either at the global or at the national level, are plentiful, especially in the grey literature. It is hotly debated whether a fully renewable energy or electricity system, with or without biomass, is possible (Jacobson et al., 2015, 2017) or not (Clack et al., 2017; Heard et al., 2017), and by what year. Scale-up estimates vary with assumptions about costs and technological maturity, as well as local geographical circumstances and the extent of storage used (REN21, 2012; Ghorbani et al., 2017). Several countries have adopted targets of 100% renewable electricity (IEA, 2017c) as this meets multiple social, economic and environmental goals and contribute to mitigation of climate change (REN21, 2012).

4.3.1.2 Bioenergy and Biofuels

Bioenergy is renewable energy from biomass. Biofuel is biomass-based energy used in transport. Chapter 2 suggests that pathways limiting warming to 1.5°C would enable supply of 67–310 (median 150) EJ yr^{-1} (see Table 2.8) from biomass. Most scenarios find that Bioenergy is combined with Carbon Dioxide Capture and Storage (CCS, BECCS) if it is available but also find robust deployment of bioenergy independent of the availability of CCS (see Section 2.3.4.2 and 4.3.7 for a discussion of BECCS). Detailed assessments indicate that deployment is similar for 2°C-consistent pathways (Chum et al., 2011; P. Smith et al., 2014; Creutzig et al., 2015). There is however *high agreement* that the sustainable bioenergy potential in 2050 would be restricted to around 100 EJ yr^{-1} (Slade et al., 2014; Creutzig et al., 2015b). Sustainable deployment at this or higher levels envisioned by 1.5°C-consistent pathways may put significant pressure on available land, food production and prices (Popp et al., 2014b; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017), preservation of ecosystems and biodiversity (Creutzig et al., 2015b; Holland et al., 2015; Santangeli et al., 2016) as well as potential water and nutrient constraints (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Bows and Smith, 2012; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratiadou et al., 2016; Smith et al., 2016b; Wei et al., 2016; Mathioudakis et al., 2017); but there is still *low agreement* on these interactions (Robledo-Abad et al., 2017). Some of the disagreement on the sustainable capacity for bioenergy stems from global versus local assessments. Global assessments may mask local dynamics that exacerbate negative impacts and shortages while at the same time niche contexts for deployment may avoid trade-offs and exploit co-benefits more effectively. In some regions of the world (e.g., the case of Brazilian ethanol, see Box 4.7, where land may be less of a constraint, the use of bioenergy is mature and the industry is well developed), land transitions could be balanced with food production and biodiversity to enable a global impact on CO_2 emissions (Jaiswal et al., 2017).

The carbon intensity of bioenergy, key for both bioenergy as an emission-neutral energy system and BECCS as a Carbon Dioxide Removal (CDR) measure, is still a matter of debate (Buchholz et al., 2016; Liu et al., 2018) and depends on management (Pyörälä et al., 2014; Torssonen et al., 2016; Baul et al., 2017; Kilpeläinen et al., 2017); direct and indirect land use change emissions (Plevin et al., 2010; Schulze et al., 2012; Harris et al., 2015; Repo et al., 2015; DeCicco et al., 2016; Qin et al., 2016)[2]; considered feedstock and time frame (Zanchi et al., 2012; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018), as well as the availability of coordinated policies and management to minimise negative side effects and trade-offs, particularly those around food security (Stevanović et al., 2017) and livelihood and equity considerations (Creutzig et al., 2013; Calvin et al., 2014) .

Biofuels are a part of the transport sector in some cities and countries, and may be deployed as a mitigation option for aviation, shipping and freight transport (see Section 4.3.3.5) as well as industrial decarbonisation (IEA, 2017g) (Section 4.3.4) though only Brazil has mainstreamed ethanol as a substantial, commercial option. Lower emissions and reduced urban air pollution have been achieved there by use of ethanol and biodiesel as fuels (Hill et al., 2006; Salvo et al., 2017) (see Box 4.7).

4.3.1.3 Nuclear Energy

Many scenarios in Chapter 2 and in AR5 (Bruckner et al., 2014) project an increase in the use of nuclear power, while others project a decrease. The increase can be realised through existing mature nuclear technologies or new options (generation III/IV reactors, breeder reactors, new uranium and thorium fuel cycles, small reactors or nuclear cogeneration).

Even though historically scalability and speed of scaling of nuclear plants have been high in many nations, such rates are currently not achieved anymore. In the 1960s and 1970s, France implemented a programme to rapidly get 80% of its power from nuclear in about 25 years (IAEA, 2018), but the current time-lag between the decision date and the commissioning of plants is observed to be 10-19 years (Lovins et al., 2018). The current deployment pace of nuclear energy is constrained by social acceptability in many countries due to concerns over risks of accidents and radioactive waste management (Bruckner et al., 2014). Though comparative risk assessment shows health risks are low per unit of electricity production (Hirschberg et al., 2016), and land requirement is lower than that of other power sources (Cheng and Hammond, 2017), the political processes triggered by societal concerns depend on the country-specific means of managing the political debates around technological choices and their environmental impacts (Gregory et al., 1993). Such differences in perception (Kim and Chung, 2017) explain why the 2011 Fukushima incident resulted in a confirmation or acceleration of phasing out nuclear energy in five countries (Roh, 2017) while 30 other countries have continued using nuclear energy, amongst which 13 are building new nuclear capacity including China, India and the United Kingdom (IAEA, 2017; Yuan et al., 2017).

Costs of nuclear power have increased over time in some developed nations, principally due to market conditions where increased investment risks of high-capital expenditure technologies have become significant. 'Learning by doing' processes often failed to compensate for this trend because they were slowed down by the absence of standardisation and series effects (Grubler, 2010). What are and have been the costs of nuclear power is debated in the literature (Lovering et al., 2016; Koomey et al., 2017). Countries with liberalised markets that continue to develop nuclear employ de-risking instruments through long-term contracts with guaranteed sale prices (Finon and Roques, 2013). For instance, the United Kingdom works with public guarantees covering part of the upfront investment costs of newly planned nuclear capacity. This dynamic differs in countries such as China and South Korea, where monopolistic conditions in the electric system allow for reducing investment risks, deploying series effects and enhancing the engineering capacities of users due to stable relations between the security authorities and builders (Schneider et al., 2017).

The safety of nuclear plants depends upon the public authorities of each country. However, because accidents affect worldwide public acceptance of this industry, questions have been raised about the risk of economic and political pressures weakening the safety of the plants (Finon, 2013; Budnitz, 2016). This raises the issue of international governance of civil nuclear risks and reinforced international cooperation involving governments, companies and engineering (Walker and Lönnroth, 1983; Thomas, 1988; Finon, 2013), based

[2] FOOTNOTE: While there is high agreement that indirect Land Use Change (iLUC) could occur, there is low agreement about the actual extent of Iluc (P. Smith et al., 2014; Verstegen et al., 2015; David, 2017)

on the experience of the International Atomic Energy Agency.

4.3.1.4 Energy Storage

The growth in electricity storage for renewables has been around Grid Flexibility Resources (GFR) that would enable several places to source more than half their power from non-hydro renewables (Komarnicki, 2016). Ten types of GFRs within smart grids have been developed largely since AR5 as renewables have tested grid stability (Blaabjerg et al., 2004; IRENA, 2013; IEA, 2017d; Majzoobi and Khodaei, 2017) though demonstrations of how to do this without hydro or natural gas-based power back-up are still needed. Pumped hydro comprised 150 GW of storage capacity in 2016, and grid-connected battery storage just 1.7 GW, but the latter grew between 2015 to 2016 by 50% (REN21, 2012). Battery storage has been the main growth feature in energy storage since AR5 (Breyer et al., 2017). This appears to the result of significant cost reductions due to mass production for Electric Vehicles (EVs) (Nykvist and Nilsson, 2015; Dhar et al., 2017). Although costs and technical maturity look increasingly positive, the feasibility of battery storage is challenged by concerns over the availability of resources and the environmental impacts of its production (Peters et al., 2017). Lithium, a common element in the earth's crust, does not appear to be restricted and large increases in production have happened in recent years with eight new mines in Western Australia where most lithium is produced (GWA, 2016). Emerging battery technologies may provide greater efficiency and recharge rates (Belmonte et al., 2016) but remain significantly more expensive due to speed and scale issues compared to lithium ion batteries (Dhar et al., 2017; IRENA, 2017a).

Research and demonstration of energy storage in the form of thermal and chemical systems continues, but large scale commercial systems are rare (Pardo et al., 2014). Renewably derived synthetic liquid (like methanol and ammonia) and gas (like methane and hydrogen) are increasingly being seen as a feasible storage options for renewable energy (producing fuel for use in industry during times when solar and wind are abundant) (Bruce et al., 2010; Jiang et al., 2010; Ezeji, 2017) but, in the case of carbonaceous storage media, would need a renewable source of carbon to make a positive contribution to GHG reduction (von der Assen et al., 2013; Abanades et al., 2017) (see also Section 4.3.4.5). The use of electric vehicles as a form of storage has been modelled and evaluated as an opportunity, and demonstrations are emerging (Dhar et al., 2017; Green and Newman, 2017a), but challenges to upscaling remain.

4.3.1.5 Options for Adapting Electricity Systems to 1.5°C

Climate change has started to disrupt electricity generation and, if climate change adaptation options are not considered, it is predicted that these disruptions will be lengthier and more frequent (Jahandideh-Tehrani et al., 2014; Bartos and Chester, 2015; Kraucunas et al., 2015; van Vliet et al., 2016). Adaptation would both secure vulnerable infrastructure and ensure the necessary generation capacity (Minville et al., 2009; Eisenack and Stecker, 2012; Schaeffer et al., 2012; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Goytia et al., 2016). The literature shows *high agreement* that climate change impacts need to be planned for in the design of any kind of infrastructure, especially in the energy sector (Nierop, 2014), including interdependencies with other sectors that require electricity to function, including water, data, telecommunications and transport (Fryer, 2017).

Recent research has developed new frameworks and models that aim to assess and identify vulnerabilities in energy infrastructure and create more proactive responses (Francis and Bekera, 2014; Ouyang and Dueñas-Osorio, 2014; Arab et al., 2015; Bekera and Francis, 2015; Knight et al., 2015; Jeong and An, 2016; Panteli et al., 2016; Perrier, 2016; Erker et al., 2017; Fu et al., 2017). Assessments of energy infrastructure adaptation, while limited, emphasise the need for redundancy (Liu et al. 2017). The implementation of controllable and islandable microgrids including the use of residential batteries, and can increase resiliency, especially after extreme weather events (Qazi and Young Jr., 2014; Liu et al., 2017). Hybrid renewables-based power systems with non-hydro capacity, such as with high-penetration wind generation, could provide the required system flexibility (Canales et al., 2015). Overall, there is *high agreement* that hybrid systems, taking advantage of an array of sources and time of use strategies, can help make electricity generation more resilient (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016).

Interactions between water and energy are complex (IEA, 2017g). Water scarcity patterns and electricity disruptions will differ across regions. There is *high agreement* that mitigation and adaptation options for thermal electricity generation (if that remains fitted with CCS) need to consider increasing water shortages, taking into account other factors such as ambient water resources and demand changes in irrigation water (Hayashi et al., 2018). Increasing the efficiency of power plants can reduce emissions and water needs (Eisenack and Stecker, 2012; van Vliet et al., 2016), but applying CCS would increase water consumption (Koornneef et al 2012). The technological, economic, social and institutional feasibility of efficiency improvements is high, but insufficient to limit temperature rise to 1.5°C (van Vliet et al., 2016).

In addition, a number of options for water cooling management systems have been proposed, such as hydraulic measures (Eisenack and Stecker, 2012) and alternative cooling technologies (Chandel et al., 2011; Eisenack and Stecker, 2012; Bartos and Chester, 2015; Murrant et al., 2015; Bustamante et al., 2016; van Vliet et al., 2016; Huang et al., 2017b). There is *high agreement* on the technological and economic feasibility of these technologies as their absence can severely impact the functioning of the power plant as well as safety and security standards.

4.3.1.6 Carbon Dioxide Capture and Storage in the Power Sector

The AR5 (IPCC, 2014b) as well as Section 2.4.2 assign significant emission reductions over the course of this century to CO_2 capture and storage (CCS) in the power sector. This section focuses on CCS in the fossil-fuelled power sector; Section 4.3.4 discusses CCS in non-power industry, and Section 4.3.7 bioenergy with CCS (BECCS). Section 2.4.2 puts the cumulative CO_2 stored from fossil-fuelled power at 410 (199–470 interquartile range) $GtCO_2$ over this century. Such modelling suggests that CCS in the power sector can contribute to cost-effective achievement of emission reduction requirements for limiting warming to 1.5°C. CCS may also offer employment and political advantages for fossil fuel-dependent economies (Kern et al., 2016), but may entail more limited co-benefits than other mitigation options (that, e.g., generate power) and therefore for its business case and economic feasibility relies on climate policy incentives. Since 2017, two CCS projects in the power sector capture 2.4 $MtCO_2$ annually, while 30 $MtCO_2$ is captured annually in all CCS projects (Global CCS Institute, 2017).

The technological maturity of CO_2 capture options in the power sectors has improved considerably (Abanades et al., 2015; Bui et al., 2018), but costs have not come down between 2005 and 2015 due to limited learning in commercial settings and increased energy and resources costs (Rubin et al., 2015). Storage capacity estimates vary greatly, but Section 2.4.2 as well as literature (V. Scott et al., 2015) indicate that perhaps 10,000 $GtCO_2$ could be stored in underground reservoirs. Regional availability of this may not be sufficient, and it requires efforts to have this storage and the corresponding infrastructure available at the necessary rates and times (de Coninck and Benson, 2014). CO_2 retention in the storage reservoir was recently assessed as 98% over 10,000 years for well-managed reservoirs, and 78% for poorly regulated ones Alcade et al 2018. A paper reviewing 42 studies on public perception of CCS (Seigo et al., 2014) found that social acceptance of CCS is predicted by trust, perceived risks and benefits. The technology itself mattered less than the social context of the project. Though insights on communication of CCS projects to the general public and inhabitants of the area around the CO_2 storage sites have been documented over the years, project stakeholders are not consistently implementing these lessons, although some projects have observed good practices (Ashworth et al., 2015).

CCS in the power sector is hardly being realised at scale, mainly because the incremental costs of capture, and the development of transport and storage infrastructures are not sufficiently compensated by market or government incentives (IEA, 2017c). In both full-scale projects in the power sector, part of the capture costs are compensated for by revenues from Enhanced Oil Recovery (EOR) (Global CCS Institute, 2017), demonstrating that EOR helps developing CCS further. EOR is a technique that uses CO_2 to mobilise more oil out of depleting oil fields, leading to additional CO_2 emissions by combusting the additionally recovered oil (Cooney et al., 2015).

4.3.2 Land and Ecosystem Transitions

This section assesses the feasibility of mitigation and adaptation options related to land use and ecosystems. Land transitions are grouped around agriculture and food, ecosystems and forests, and coastal systems.

4.3.2.1 Agriculture and Food

In a 1.5°C world, local yields are projected to decrease in tropical regions that are major food producing areas of the world (West Africa, South-East Asia, South-Asia, and Central and northern South America) (Schleussner et al., 2016). Some high-latitude regions may benefit from the combined effects of elevated CO_2 and temperature because their average temperatures are below optimal temperature for crops. In both cases there are consequences for food production and quality (Cross-Chapter Box 6 in Chapter 3 on Food Security), conservation agriculture, irrigation, food wastage, bioenergy and the use of novel technologies.

Food production and quality. Increased temperatures, including 1.5°C warming, would affect the production of cereals such as wheat and rice, impacting food security (Schleussner et al., 2016). There is *medium agreement* that elevated CO_2 concentrations can change food composition, with implications for nutritional security (Taub et al., 2008; Högy et al., 2009; DaMatta et al., 2010; Loladze, 2014; De Souza et al., 2015), with the effects being different depending on the region (Medek et al., 2017).

Meta-analyses of the effects of drought, elevated CO_2, and temperature conclude that at 2°C local warming and above, aggregate production of wheat, maize, and rice are expected to decrease in both temperate and tropical areas (Challinor et al., 2014). These production losses could be lowered if adaptation measures are taken (Challinor et al., 2014), such as developing varieties better adapted to changing climate conditions.

Adaptation options can help ensure access to sufficient, quality food. These include conservation agriculture, improved livestock management, increasing irrigation efficiency, agroforestry and management of food loss and waste. Complementary adaptation and mitigation options, for example, the use of climate services (Section 4.3.5), bioenergy (Section 4.3.1) and biotechnology (Section 4.4.4) can also serve to reduce emissions intensity and the carbon footprint of food production.

Conservation Agriculture (CA). Soil management that reduces the disruption of soil structure and biotic processes by minimising tillage. A recent meta-analysis showed that no-till practices work well in water-limited agroecosystems when implemented jointly with residue retention and crop rotation but may by themselves decrease yields in other situations (Pittelkow et al., 2014). Additional climate adaptations include adjusting planting times and crop varietal selection and improving irrigation efficiency. Adaptations such as these may increase wheat and maize yields by 7–12% under climate change (Challinor et al., 2014). CA can also help build adaptive capacity (*medium evidence, medium agreement)* (H. Smith et al., 2017; Pradhan et al., 2018) and have mitigation co-benefits through improved fertiliser use or efficient use of machinery and fossil fuels (Harvey et al., 2014; Cui et al., 2018; Pradhan et al., 2018). CA practices can also raise soil carbon and therefore remove CO_2 from the atmosphere (Poeplau and Don 2015; Vicente-Vicente et al. 2016; Aguilera et al. 2013). However, CA adoption can be constrained by inadequate institutional arrangements and funding mechanisms (Harvey et al., 2014; Baudron et al., 2015; Li et al., 2016; Dougill et al., 2017; Smith et al., 2017b).

Sustainable intensification of agriculture consists of agricultural systems with increased production per unit area but with management of the range of potentially adverse impacts on the environment (Pretty and Bharucha, 2014). Sustainable intensification can increase the efficiency of inputs and enhance health and food security (Ramankutty et al., 2018).

Livestock management. Livestock are responsible for more GHG emissions than all other food sources.

Emissions are caused by feed production, enteric fermentation, animal waste, land-use change and livestock transport and processing. Some estimates indicate that livestock supply chains could account for 7.1 $GtCO_2$, equivalent to 14.5% of global anthropogenic greenhouse gas emissions (Gerber et al., 2013). Cattle (beef, milk) are responsible for about two-thirds of that total, largely due to methane emissions resulting from rumen fermentation (Gerber et al., 2013; Opio et al., 2013).

Despite ongoing gains in livestock productivity and volumes, the increase of animal products in global diets is restricting overall agricultural efficiency gains because of inefficiencies in the conversion of agricultural primary production (e.g., crops) in the feed-animal products pathway (Alexander et al., 2017), offsetting the benefits of improvements in livestock production systems (Clark and Tilman, 2017).

There is increasing agreement that overall emissions from food systems could be reduced by targeting the demand for meat and other livestock products, particularly where consumption is higher than suggested by human health guidelines. Adjusting diets to meet nutritional targets could bring large co-benefits, through GHG mitigation and improvements in the overall efficiency of food systems (Erb et al., 2009; Tukker et al., 2011; Tilman and Clark, 2014; van Dooren et al., 2014; Ranganathan et al., 2016). Dietary shifts could contribute one-fifth of the mitigation needed to hold warming below 2°C, with one-quarter of low-cost options (Griscom et al., 2017). There, however, remains limited evidence of effective policy interventions to achieve such large-scale shifts in dietary choices, and prevailing trends are for increasing rather than decreasing demand for livestock products at the global scale (Alexandratos and Bruinsma, 2012; OECD/FAO, 2017). How the role of dietary shift could change in 1.5°C-consistent pathways is also not clear (see Chapter 2).

Adaptation of livestock systems can include a suite of strategies such as using different breeds and their wild relatives to develop a genetic pool resilient to climatic shocks and longer-term temperature shifts (Thornton and Herrero, 2014), improving fodder and feed management (Bell et al., 2014; Havet et al., 2014) and disease prevention and control (Skuce et al., 2013; Nguyen et al., 2016). Most interventions that improve the productivity of livestock systems and enhance adaptation to climate changes would also reduce the emissions intensity of food production, with significant co-benefits for rural livelihoods and security of food supply (Gerber et al., 2013; FAO & NZAGRC, 2017a, 2017b, 2017c). Whether such reductions in emission intensity result in lower or higher absolute GHG emissions depends on overall demand for livestock products, indicating the relevance of integrating supply-side with demand-side measures within food security objectives (Gerber et al., 2013; Bajželj et al., 2014). Transitions in livestock production systems (e.g., from extensive to intensive) can also result in significant emission reductions as part of broader land-based mitigation strategies (Havlik et al., 2014).

Overall, there is *high agreement* that farm strategies that integrate mixed crop-livestock systems can improve farm productivity and have positive sustainability outcomes (Havet et al., 2014; Thornton and Herrero, 2014; Herrero et al., 2015; Weindl et al., 2015). Shifting towards mixed crop-livestock systems is estimated to reduce agricultural adaptation costs to 0.3% of total production costs while abating deforestation by 76 million ha globally, making it a highly cost-effective adaptation option with mitigation co-benefits (Weindl et al., 2015). Evidence from various regions supports this (Thornton and Herrero, 2015), although the feasible scale varies between regions and systems, as well as being moderated by overall demand in specific food products. In Australia, some farmers have successfully shifted to crop-livestock systems where, each year, they allocate land and forage resources in response to climate and price trends (Bell et al., 2014) . However, there can be some unintended negative impacts of such integration, including an increased burdens on women, higher requirements of capital, competing uses of crop residues (e.g., feed vs. mulching vs. carbon sequestration) and higher requirements of management skills, which can be a challenge across several low income countries (Thornton and Herrero, 2015; Thornton et al., 2018). Finally, the feasibility of improving livestock efficiency is dependent on socio-cultural context and acceptability: there remain significant issues around widespread adoption of crossbred animals, especially by smallholders (Thornton et al., 2018).

Irrigation efficiency. Irrigation efficiency is especially critical since water endowments are expected to change, with 20–60 Mha of global cropland being projected to revert from irrigated to rain fed land, while other areas will receive higher precipitation in shorter time spans thus affecting irrigation demand (Elliott et al., 2014). While increasing irrigation system efficiency is necessary, there is mixed evidence on how to enact efficiency improvements (Fader et al., 2016; Herwehe and Scott, 2017). Physical and technical strategies include building large-scale reservoirs or dams, renovating or deepening irrigation channels, building on-farm rainwater harvesting structures, lining ponds, channels and tanks to reduce losses through percolation and evaporation, and investing in small infrastructure such as sprinkler or drip irrigation sets (Varela-Ortega et al., 2016; Sikka et al., 2018). Each strategy has differing costs and benefits relating to unique biophysical, social, and economic contexts. Other concerns relating to the increase of irrigation efficiency discuss fostering irrigation dependency, hence increasing climate sensitivity, which may be maladaptive in the long-term (Lindoso et al., 2014).

Improvements in irrigation efficiency would need to be supplemented with ancillary activities, such as shifting to crops that require less water, and improving soil and moisture conservation (Fader et al., 2016; Hong and Yabe, 2017; Sikka et al., 2018). Currently, the feasibility of improving irrigation efficiency is constrained by issues of replicability across scale and sustainability over time (Burney and Naylor, 2012), institutional barriers and inadequate market linkages (Pittock et al., 2017).

Growing evidence suggests that investing in behavioural shifts towards using irrigation technology such as micro-sprinklers or drip irrigation, is an effective and quick adaptation strategy (Varela-Ortega et al., 2016; Herwehe and Scott, 2017; Sikka et al., 2018) as opposed to large dams which have high financial, ecological and social costs (Varela-Ortega et al., 2016). While improving irrigation efficiency is technically feasible (R. Fishman et al., 2015) and has clear benefits for environmental values (Pfeiffer and Lin, 2014; R. Fishman et al., 2015), feasibility is regionally differentiated as shown by examples as diverse as Kansas (Jägermeyr et al., 2015), India (R. Fishman et al., 2015) and Africa (Pittock et al., 2017).

Agroforestry. The integration of trees and shrubs into crop and livestock systems, when properly managed, can potentially restrict soil erosion, facilitate water infiltration, improve soil physical properties and buffer against extreme events (Lasco et al., 2014; Mbow et al., 2014; Quandt et al., 2017; Sida et al., 2018). There is *medium evidence* and *high agreement* on the feasibility of agroforestry practices that enhance productivity, livelihoods and carbon storage (Lusiana et al., 2012; K Murthy, 2013; Coulibaly et al., 2017; Sida et al., 2018), including from indigenous production systems (Coq-Huelva et al., 2017), with variation by region, agroforestry type, and climatic conditions (Place et al., 2012; Coe et al., 2014; Mbow et al., 2014; Iiyama et al., 2017; Abdulai et al., 2018). Long-term studies examining the success of agroforestry, however, are rare (Coe et al., 2014; Meijer et al., 2015; Brockington et al., 2016; Zomer et al., 2016).

The extent to which agroforestry practices at farm-level could be scaled up globally while satisfying growing food demand is relatively unknown. Agroforestry adoption has been relatively low and uneven (Jacobi et al., 2017; Hernández-Morcillo et al., 2018), with constraints including the expense of establishment and lack of reliable financial support, insecure land tenure, landowner's lack of experience with trees, complexity of management practices, fluctuating market demand and prices for different food and fibre products, the time and knowledge required for management, low intermediate benefits to offset revenue lags, and inadequate market access (Pattanayak et al., 2003; Mercer, 2004; Sendzimir et al., 2011; Valdivia et al., 2012; Coe et al., 2014; Meijer et al., 2015; Coulibaly et al., 2017; Jacobi et al., 2017).

Managing food loss and waste. The way food is produced, processed and transported strongly influences GHG emissions. Around one-third of the food produced on the planet is not consumed (FAO, 2013) affecting food security and livelihoods (See Cross-Chapter Box 6 on Food Security in Chapter 3). Food wastage is a combination of food loss–decrease in mass and nutritional value of food due to poor infrastructure, logistics, and lack of storage technologies and management – and food waste that derives from inappropriate human consumption that leads to food spoilage associated with inferior quality or overproduction. Food wastage could lead to an increase in emissions estimated to 1.9–2.5 $GtCO_2$-eq yr^{-1} (Hiç et al., 2016).

Decreasing food wastage has high mitigation and adaptation potential and could play an important role in land transitions towards 1.5°C, provided that reduced food waste results in lower production-side emissions rather than increased consumption (Foley et al., 2011). There is *medium agreement* that a combination of individual-institutional behaviour (Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014), and improved technologies and management (Lin et al., 2013; Papargyropoulou et al., 2014) can transform food waste into products with marketable value. Institutional behaviour depends on investment and policies, which if adequately addressed could enable mitigation and adaptation co-benefits, in a relatively short time.

Novel technologies. New molecular biology tools have been developed that can lead to fast and precise genome modification (De Souza et al., 2016; Scheben et al., 2016) (e.g., CRISPR Cas 9 (Ran et al., 2013; Schaeffer and Nakata, 2015). Such genome editing tools may moderately assist in mitigation and adaptation of agriculture in relation to climate changes, CO_2 elevation, drought and flooding (DaMatta et al., 2010; De Souza et al., 2015, 2016). These tools could contribute to developing new plant varieties that can adapt to warming of 1.5°C and overshoot, potentially avoiding some of the costs of crop shifting (Schlenker and Roberts, 2009; De Souza et al., 2016). However, biosafety concerns and government regulatory systems can be a major barrier to the use of these tools as this increases the time and cost of turning scientific discoveries into ready applicable technologies (Andow and Zwahlen, 2006; Maghari and Ardekani, 2011).

The strategy of reducing enteric methane emissions by ruminants through the development of inhibitors or vaccines has already been attempted with some successes, although the potential for application at scale and in different situations remains uncertain. A methane inhibitor has been demonstrated to reduce methane from feedlot systems by 30% over a 12-week period (Hristov et al., 2015) with some productivity benefits but the ability to apply it in grazing systems will depend on further technological developments as well as costs and incentives. A vaccine could potentially modify the microbiota of the rumen and be applicable even in extensive grazing systems by reducing the presence of methanogenic micro-organisms (Wedlock et al., 2013) but has not yet been successfully demonstrated to reduce emissions in live animals. Selective breeding for lower-emitting ruminants is becoming rapidly feasible, offering small but cumulative emissions reductions without requiring substantial changes in farm systems (Pickering et al., 2015).

Technological innovation in culturing marine and freshwater micro and macro flora has significant potential to expand food, fuel and fibre resources, and could reduce impacts on land and conventional agriculture (Greene et al., 2017).

Technological innovation could assist in increased agricultural efficiency (e.g., via precision agriculture), decrease food wastage and genetics that enhance plant adaptation traits (Section 4.4.4). Technological and associated management improvements may be ways to increase the efficiency of contemporary agriculture to help produce enough food to cope with population increases in a 1.5°C warmer world, and help reduce the pressure on natural ecosystems and biodiversity.

4.3.2.2 Forests and Other Ecosystems

Ecosystem restoration. Biomass stocks in tropical, subtropical, temperate and boreal biomes currently hold 1085, 194, 176, 190 Gt CO_2, respectively. Conservation and restoration can enhance these natural carbon sinks (Erb et al., 2017).

Recent studies explore options for conservation, restoration and improved land management estimating up to 23 $GtCO_2$ (Griscom et al., 2017). Mitigation potentials are dominated by reduced rates of deforestation, reforestation and forest management, and concentrated in tropical regions (Houghton, 2013; Canadell and Schulze, 2014; Grace et al., 2014; Houghton et al., 2015; Griscom et al., 2017). Much of the literature focuses on REDD+ (Reducing Emissions from Deforestation and Degradation) as an institutional mechanism. However, restoration and management activities need not be limited to REDD+ and locally adapted implementation may keep costs low, capitalise on co-benefits and ensure consideration of competing for socio-economic goals (Jantke et al., 2016; Ellison et al., 2017; Perugini et al., 2017; Spencer et al., 2017).

Half of the estimated potential can be achieved at <100 USD/tCO_2; a third of the cost-effective potential <10 USD/tCO_2 (Griscom et al., 2017). Variation of costs in projects aiming to reduce emissions from deforestation is high when considering opportunity and transaction costs (Dang Phan et al., 2014; Overmars et al., 2014; Ickowitz et al., 2017; Rakatama et al., 2017).

However, the focus on forests raises concerns of cross-biome leakage *(medium evidence, low agreement)* (Popp et al., 2014a; Strassburg et al., 2014; Jayachandran et al., 2017) and encroachment on other ecosystems (Veldman et al., 2015). Reducing rates of deforestation limits the land available for agriculture and grazing with trade-offs between diets, higher yields and food prices (Erb et al., 2016a; Kreidenweis et al., 2016). Restoration and conservation are compatible with biodiversity (Rey Benayas et al., 2009; Jantke et al., 2016) and water resources; in the tropics, reducing rates of deforestation maintains cooler surface temperatures (Perugini et al., 2017) and rainfall (Ellison et al., 2017).

Its multiple potential co-benefits have made REDD+ important for local communities, biodiversity and sustainable landscapes (Ngendakumana et al., 2017; Turnhout et al., 2017). There is *low agreement* on whether climate impacts will reverse mitigation benefits of restoration (Le Page et al., 2013) by increasing the likelihood of disturbance (Anderegg 2015), or reinforce them through carbon fertilisation (P. Smith et al., 2014).

Emerging regional assessments offer new perspectives for upscaling. Strengthening coordination, additional funding sources, and access and disbursement points increase the potential of REDD+ in working towards 2°C and 1.5°C targets (Well and Carrapatoso, 2017). While there are indications that land tenure (Sunderlin et al., 2014) has a positive impact, a meta-analysis by (Wehkamp et al., 2018a) shows that there is *medium evidence* and *low agreement* on which aspects of governance improvements are supportive of conservation. Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case (Sunderlin et al., 2014; Brugnach et al., 2017). Although payments for reduced rates of deforestation may benefit the poor, the most vulnerable populations could have limited, uneven access (Atela et al., 2014) and face lower opportunity costs from deforestation (Ickowitz et al., 2017).

Community-based Adaptation (CbA). There is *medium evidence* and *high agreement* for the use of CbA. The specific actions to take will depend upon the location, context, and vulnerability of the specific community. CbA is defined as ‘a community-led process, based on communities' priorities, needs, knowledge, and capacities, which aim to empower people to plan for and cope with the impacts of climate change’ (Reid et al., 2009). The integration of CbA with Ecosystems-based Adaptation (EbA) has been increasingly promoted, especially in efforts to alleviate poverty (Mannke, 2011; Reid, 2016).

Despite the potential and advantages of both CbA and EbA, including knowledge exchange, information access and increased social capital and equity; institutional and governance barriers still constitute a challenge for local adaptation efforts (Wright et al., 2014; Fernández-Giménez et al., 2015).

Wetland management. In wetland ecosystems, temperature rise has direct and irreversible impacts on species functioning and distribution, ecosystem equilibrium and services, and second order impacts on local livelihoods (see Section 3.4.3). The structure and function of wetland systems are changing due to climate change. Wetland management strategies, including adjustments in infrastructural, behavioural, and institutional practices have clear implications for adaptation (Colloff et al., 2016b; Finlayson et al., 2017; Wigand et al., 2017)

Despite international initiatives on wetland restoration and management through the Ramsar Convention on Wetlands, policies have not been effective (Finlayson, 2012; Finlayson et al., 2017). Institutional reform such as flexible, locally relevant governance, drawing on principles of adaptive co-management, and multi-stakeholder participation becomes increasingly necessary for effective wetland management (Capon et al., 2013; Finlayson et al., 2017).

4.3.2.3 Coastal Systems

Managing coastal stress. Particularly to allow for the landward relocation of coastal ecosystems under a transition to 1.5°C, planning for climate change would need to be integrated with the use of coastlines by humans (Saunders et al., 2014; Kelleway et al., 2017). Adaptation options for managing coastal stress include coastal hardening through the building of seawalls and the re-establishment of coastal ecosystems such as mangroves (André et al., 2016; Cooper et al., 2016). While the feasibility of the solutions is high, they are expensive to scale (*robust evidence, medium agreement*).

There is *low evidence* and *high agreement* that reducing the impact of local stresses (Halpern et al., 2015) will improve the resilience of marine ecosystems as they transition to a 1.5°C world (O'Leary et al., 2017). Approaches to reducing local stresses are considered feasible, cost-effective and highly scalable. Ecosystem resilience may be increased through alternative livelihoods (e.g., sustainable aquaculture), which are among a suite of options for building resilience in coastal ecosystems. These options enjoy high levels of feasibility yet are expensive, which stands in the way of scalability (*robust evidence, medium agreement*) (Hiwasaki et al., 2015; Brugnach et al., 2017).

Working with coastal communities has the potential for improving the resilience of coastal ecosystems. Combined with the advantages of using Indigenous knowledge to guide transitions, solutions can be more effective when undertaken in partnership local communities, cultures, and knowledge (See Box 4.3).

Restoration of coastal ecosystems and fisheries. Marine restoration is expensive compared to terrestrial restoration, and the survival of projects is currently low, with success depending on the ecosystem and site, rather than the size of the financial investment (Bayraktarov et al., 2016). Mangrove replanting shows evidence of success globally, with numerous examples of projects that have established forests (Kimball et al., 2015; Bayraktarov et al., 2016).

Efforts with reef-building corals have been attempted with a low level of success (Bayraktarov et al., 2016). Technologies to help re-establish coral communities are limited (Rinkevich, 2014), as are largely untested disruptive technologies (e.g., genetic manipulation, assisted evolution) (van Oppen et al., 2015). Current technologies also have trouble scaling given the substantial costs and investment required (Bayraktarov et al., 2016).

(Johannessen and Macdonald, 2016) report the 'blue carbon' sink to be 0.4–0.8% of global anthropogenic emissions. However, this does not adequately account for post-depositional processes and could overestimate removal potentials, subject to a risk of reversal. Seagrass beds will thus not contribute significantly to enabling 1.5°C-consistent pathways.

4.3.3 Urban and Infrastructure System Transitions

There will be approximately 70 million additional urban residents every year through to the mid part of this century (UN, 2014). The majority of these new urban citizens will reside in small and medium sized cities in low- and middle-income countries (Cross-Chapter Box13 in Chapter 5). The combination of urbanisation and economic and infrastructure development could account for an additional 226 $GtCO_2$ by 2050 (Bai et al. 2018). However, urban systems can harness the mega-trends of urbanisation, digitalisation, financialisation and growing sub-national commitment to smart cities, green cities, resilient cities, sustainable cities and adaptive cities, for the type of transformative change required by 1.5°C-consistent pathways (Revi and Rosenzweig, 2013; Parag and Sovacool, 2016; Roberts, 2016; Wachsmuth et al., 2016; Revi, 2017; Solecki et al., 2018). There is a growing number of urban climate responses driven by cost-effectiveness, development, work creation and inclusivity considerations (Floater et al., 2014; Revi et al., 2014a; Villarroel Walker et al., 2014; Kennedy et al., 2015; Rodríguez, 2015; Newman et al., 2017; UN-Habitat, 2017; Westphal et al., 2017) (Solecki et al. 2013; Ahern et al. 2014; McGranahan et al. 2016; Dodman et al. 2017a).

In addition, low-carbon cities could reduce the need to deploy Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) (Fink, 2013; Thomson and Newman, 2016).

Cities are also places in which the risks associated with warming of 1.5°C, such as heat stress, terrestrial and coastal flooding, new disease vectors, air pollution and water scarcity, will coalesce (see Section 3.3) (Dodman et al., 2017a; Satterthwaite and Bartlett, 2017). Unless adaptation and mitigation efforts are designed around the need to decarbonise urban societies in the developed world and provide low-carbon solutions to the needs of growing urban populations in developing countries, they will struggle to deliver the pace or scale of change required by 1.5°C-consistent pathways (Hallegatte et al., 2013; Villarroel Walker et al., 2014; Roberts, 2016; Solecki et al., 2018). The pace and scale of urban climate responses can be enhanced by attention to social equity (including gender equity), urban ecology (Brown and McGranahan, 2016; Wachsmuth et al., 2016; Ziervogel et al., 2016a) and participation in sub-national networks for climate action (Cole, 2015; Jordan et al., 2015).

The long-lived urban transport, water and energy systems that will be constructed in the next three decades to support urban populations in developing countries and to retrofit cities in developed countries will have to be different to that built in Europe and North America in the 20th century, if they are to support the required transitions (Freire et al., 2014; Cartwright, 2015; McPhearson et al., 2016; Roberts, 2016; Lwasa, 2017). Recent literature identifies energy, infrastructure, appliances, urban planning, transport and adaptation options as capable of facilitating systemic change. It is these aspects of the urban system that are discussed below and from which options in Section 4.5 are selected.

4.3.3.1 Urban Energy Systems

Urban economies tend to be more energy intensive than national economies due to higher levels of *per capita* income, mobility and consumption (Kennedy et al., 2015; Broto, 2017; Gota et al., 2018). However, some urban systems have begun decoupling development from the consumption of fossil fuel powered energy through energy efficiency, renewable energy and locally managed smart-grids (Dodman, 2009; Freire et al., 2014; Eyre et al., 2018; Glazebrook and Newman, 2018a).

The rapidly expanding cities of Africa and Asia, where energy poverty currently undermines adaptive capacity (Westphal et al., 2017; Satterthwaite et al., 2018), have the opportunity to benefit from recent price changes in renewable energy technologies to enable clean energy access to citizens (SDG 7) (Cartwright, 2015; Watkins, 2015; Lwasa, 2017; Kennedy et al., 2018; Teferi and Newman, 2018). This will require strengthened energy governance in these countries (Eberhard et al., 2017). Where renewable energy displaces paraffin, wood fuel or charcoal feedstocks in informal urban settlements, it provides the co-benefits of improved indoor air quality, reduced fire-risk and reduced deforestation, all of which can enhance adaptive capacity and strengthen demand for this energy (Newham and Conradie, 2013; Winkler, 2017; Kennedy et al., 2018; Teferi and Newman, 2018).

4.3.3.2 Urban Infrastructure, Buildings and Appliances

Buildings are responsible for 32% of global energy consumption (IEA, 2016c) and have a large energy saving potential with available and demonstrated technologies such as energy efficiency improvements in technical installations and in thermal insulation (Toleikyte et al., 2018) and energy sufficiency (Thomas et al., 2017). (Kuramochi et al., 2017) show that 1.5°C-consistent pathways require building emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020, and an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD (Organisation for Economic Co-operation and Development) countries (see also Section 4.2.1).

Chapter 2 based on the IEA-ETP (IEA, 2017g) identifies large saving potential in heating and cooling through improved building design, efficient equipment, lighting and appliances. Several examples of net zero energy in buildings are now available (Wells et al., 2018). In existing buildings, refurbishment enables energy saving (Semprini et al., 2017; Brambilla et al., 2018; D'Agostino and Parker, 2018; Sun et al., 2018) and cost savings (Toleikyte et al., 2018; Zangheri et al., 2018).

Reducing the embodied energy in buildings material provides further energy and GHG savings (Cabeza et al., 2013; Oliver and Morecroft, 2014; Koezjakov et al., 2018), in particular through bio-based materials (Lupíšek et al., 2015) and wood construction (Ramage et al., 2017). The United Nations Environment Programme (UNEP[3]) estimates that improving embodied energy, thermal performance, and direct energy use of buildings can reduce emissions by 1.9 $GtCO_2e\ yr^{-1}$(UNEP, 2017b), with an additional reduction of 3 $GtCO_2e\ yr^{-1}$ through energy efficient appliances and lighting (UNEP, 2017b). Further increasing the energy efficiency of appliances and lighting, heating and cooling offers the potential for further savings (Parikh and Parikh, 2016; Garg et al., 2017).

Smart technology, drawing on the Internet of Things (IoT) and building information modelling, offer opportunities to accelerate energy efficiency in buildings and cities (Moreno-Cruz and Keith, 2013; Hoy, 2016) (see also Section 4.4.4). Some developing country cities are drawing on these technologies to adopt 'leapfrog' infrastructure, buildings and appliances to pursue low-carbon development (Newman et al., 2017; Teferi and Newman, 2017) (Cross-Chapter Box 13 in Chapter 5).

4.3.3.3 Urban Transport and Urban Planning

Urban form impacts demand for energy (Sims et al., 2014) and other welfare related factors: a meta-analysis of 300 papers reported energy savings of 26 USD per person per year attributable to a 10% increase in urban population density (Ahlfeldt and Pietrostefani, 2017). Significant reductions in car use are associated with dense, pedestrianised cities and towns and medium-density transit corridors (Newman and Kenworthy, 2015; Newman et al., 2017) relative to low-density cities in which car dependency is high (Kenworthy and Schiller, 2018). Combined dense urban forms and new mass transit systems in Shanghai and Beijing have yielded less car use (Gao and Newman, 2018) (see Box 4.9). Compact cities also create the passenger density required to make public transport more financially viable (Ahlfeldt and Pietrostefani, 2017; Rode et al., 2017) and enable combinations of cleaner fuel feed stocks and urban smart-grids, in which vehicles form part of the storage capacity (Oldenbroek et al., 2017). Similarly, the spatial organisation of urban energy influenced the trajectories of urban development in cities as diverse as Hong Kong, Bengaluru and Maputo (Broto, 2017).

The informal settlements of middle- and low-income cities where urban density is more typically associated with a range of water- and vector-borne health risks, may provide a notable exception to the adaptive advantages of urban density (Mitlin and Satterthwaite, 2013; Lilford et al., 2017) unless new approaches and technologies are harnessed to accelerate slum upgrading (Teferi and Newman, 2017)

Scenarios consistent with 1.5°C pathways, depend on an almost 40% reduction in final energy use by the transport sector by 2050 (Chapter 2, Figure 2.12). In one analysis the phasing out of fossil fuel passenger vehicle sales by 2035-2050 was identified as a benchmark for aligning with 1.5°C-consistent pathways (Kuramochi et al., 2017). Reducing emissions from transport has lagged the power sector (Sims et al., 2014; Creutzig et al., 2015a) but evidence since AR5 suggests that cities are urbanising and re-urbanising in ways that co-ordinate transport sector adaptation and mitigation (Colenbrander et al., 2017; Newman et al., 2017; Salvo et al., 2017; Gota et al., 2018). The global transport sector could reduce 4.7$GtCO2e\ yr^{-1}$ (4.1–5.3) by 2030. This is significantly more than is predicted by Integrated Assessment Models (IAMs; UNEP, 2017b). Such a transition depends on cities that enable modal shifts, avoided journeys, provide incentives for uptake of improved fuel efficiency and changes in urban design that encourage walkable cities, non-motorised transport and shorter commuter distances (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In at least four African cities, 43 Asian cities and 54 Latin American cities, Transit Oriented Development (TOD), has emerged as an organising principle for urban growth and spatial planning (Colenbrander et al., 2017; Lwasa, 2017; BRT Data, 2018). This trend is important to counter the rising

[3] FOOTNOTE: Currently called UN Environment.

demand for private cars in developing country cities (OECD, 2016b). In India TOD has been combined with localized solar PV installations and new ways of financing rail expansion (Sharma, 2018).

Cities pursuing sustainable transport benefit from reduced air pollution, congestion and road fatalities and are able to harness the relationship between transport systems, urban form, urban energy intensity and social cohesion (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015; Wee, 2015)

Technology and electrification trends since AR5 make carbon efficient urban transport easier (Newman et al., 2016), but realising urban transport's contribution to a 1.5°C-consistent pathways will require the type of governance that can overcome the financial, institutional, behavioural and legal barriers to change (Geels, 2014; Bakker et al., 2017).

Adaptation to a 1.5°C world is enabled by urban design and spatial planning policies that consider extreme weather conditions and reduce displacement by climate related disasters (UNISDR, 2009; UN-Habitat, 2011; Mitlin and Satterthwaite, 2013).

Building codes and technology standards for public lighting, including traffic lights (Beccali et al., 2015), play a critical role in reducing carbon emissions, enhancing urban climate resilience and managing climate risk (Steenhof and Sparling, 2011; Parnell, 2015; Shapiro, 2016; Evans et al., 2017). Building codes can support the convergence to zero emissions from buildings (Wells et al., 2018), and can be used retrofit the existing building stock for energy efficiency (Ruparathna et al., 2016).

The application of building codes and standards for 1.5°C-consistent pathways will require improved enforcement, which can be a challenge in developing countries where inspection resources are often limited and codes are poorly tailored to local conditions (Ford et al., 2015c; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Hess and Kelman, 2017; Mavhura et al., 2017). In all countries, building codes can be undermined by industry interests, and can be maladaptive if they prevent buildings or land use from evolving to reduce climate impacts (Eisenberg, 2016; Shapiro, 2016).

The deficit in building codes and standards in middle-income and developing country cities need not be a constraint to more energy-efficient and resilient buildings (Tait and Euston-Brown, 2017). For example, the relatively high price that poor households pay for unreliable and at times dangerous household energy in African cities has driven the uptake of renewable energy and energy efficiency technologies in the absence of regulations or fiscal incentives (Eberhard et al., 2011, 2016; Cartwright, 2015; Watkins, 2015). The Kuyasa Housing Project in Khayelitsha, one of Cape Town's poorest suburbs, created significant mitigation and adaptation benefits by installing ceilings, solar water heaters and energy efficient lightbulbs in houses independent of the formal housing or electrification programme (Winkler, 2017).

4.3.3.4 Electrification of Cities and Transport

The electrification of urban systems, including transport, has shown global progress since AR5 (IEA, 2016a; Kennedy et al., 2018; Kenworthy and Schiller, 2018). High growth rates are now appearing in electric vehicles (Figure 4.1), electric bikes and electric transit (IEA, 2018), which would need to displace fossil-fuel powered passenger vehicles by 2035–2050 to remain in line with 1.5°C-consistent pathways. China's 2017 Road Map calls for 20% of new vehicle sales to be electric. India is aiming for exclusively electric vehicles (EVs) by 2032 (NITI Aayog and RMI, 2017). Globally, EV sales were up 42% in 2016 relative to 2015, and in the United States EV sales were up 36% over the same period (Johnson and Walker, 2016).

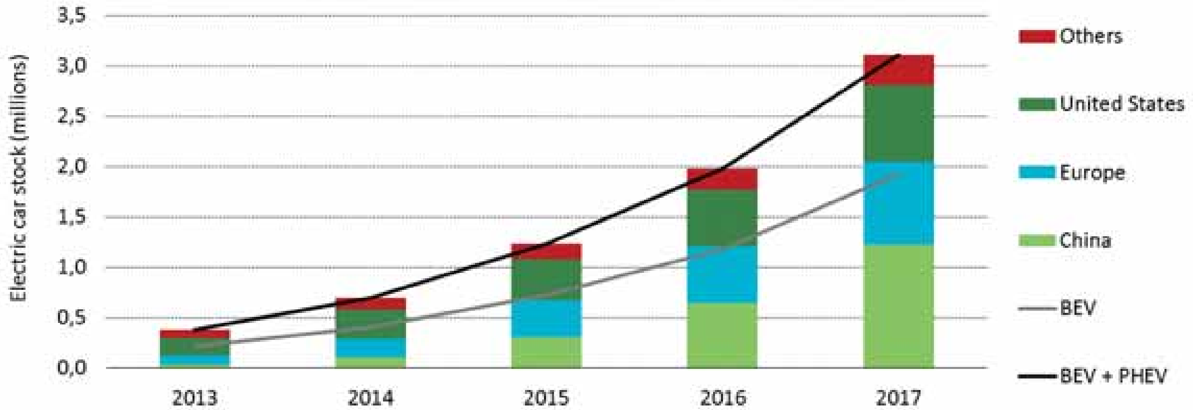

Figure 4.1: Increase of the global electric car stock by country (2013–2017). Source: (IEA, 2018). Based on IEA data from Global EV Outlook 2018 © OECD/IEA 2018, IEA Publishing.

The extent of electric railways in and between cities has expanded since AR5 (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In high income cities there is *medium evidence* for the decoupling of car use and wealth since AR5 (Newman, 2017). In cities where private vehicle ownership is expected to increase, less carbon-intensive fuel sources and reduced car journeys will be necessary as well as electrification of all modes of transport (Mittal et al., 2016; van Vuuren et al., 2017). Some recent urban data show a decoupling of urban growth and GHG emissions (Newman and Kenworthy, 2015) and that 'peak car' has been reached in Shanghai and Beijing (Gao and Kenworthy, 2017) and beyond (Manville et al., 2017) (also see Box 4.9).

An estimated 800 cities globally have operational bike-share schemes (E. Fishman et al., 2015) and China had 250 million e-bikes in 2017 (Newman et al., 2017). Advances in Information and Communication Technologies (ICT) offer cities the chance to reduce urban transport congestion and fuel consumption by making better use of the urban vehicle fleet through car sharing, driverless cars and coordinated public transport, especially when electrified (Wee, 2015; Glazebrook and Newman, 2018b). Advances in 'big-data' can assist in creating a better understanding of the connections between cities, green infrastructure, environmental services and health (Jennings et al., 2016) and improve decision-making in urban development (Lin et al., 2017).

4.3.3.5 Shipping, Freight and Aviation

International transport hubs, including airports and ports and the associated mobility of people, are major economic contributors to most large cities even while under the governance of national authorities and international legislation. Shipping, freight and aviation systems have grown rapidly and little progress has been made since AR5 on replacing fossil fuels, though some trials are continuing (Zhang, 2016; Bouman et al., 2017; EEA, 2017). Aviation emissions do not yet feature in IAMs (Bows-Larkin, 2015), but could be reduced by between a third and two-thirds through energy efficiency measures and operational changes (Dahlmann et al., 2016). On shorter inter-city trips, aviation could be replaced by high-speed electric trains drawing on renewable energy (Åkerman, 2011). Some progress has been made on the use of electricity in planes and shipping (Grewe et al., 2017) though no commercial applications have arisen. Studies indicate that biofuels are the most viable means of decarbonising intercontinental travel, given their technical characteristics, energy content and affordability (Wise et al., 2017). The lifecycle emissions of bio-based jet fuels and marine fuels can be considerable (Cox et al., 2014; IEA, 2017g) depending on their location (Elshout et al., 2014), but can be reduced by feedstock and conversion technology choices (de Jong et al., 2017).

In recent years the potential for transport to use synfuels, such as ethanol, methanol, methane, ammonia and hydrogen, created from renewable electricity and CO_2, has gained momentum but has not yet demonstrated benefits on a scale consistent with 1.5ºC pathways (Ezeji, 2017; Fasihi et al., 2017). Decarbonising the fuel used by the world's 60,000 large vessels faces governance barriers and the need for a global policy (Bows and Smith, 2012; IRENA, 2015; Rehmatulla and Smith, 2015). Low-emission marine fuels could simultaneously address sulphur and black carbon issues in ports and around waterways and accelerate the electrification of all large ports (Bouman et al., 2017; IEA, 2017g).

4.3.3.6 Climate-Resilient Land Use

Urban land use influences energy intensity, risk exposure and adaptive capacity (Carter et al., 2015; Araos et al., 2016a; Ewing et al., 2016; Newman et al., 2016; Broto, 2017). Accordingly, urban land-use planning can contribute to climate mitigation and adaptation (Parnell, 2015; Francesch-Huidobro et al., 2017) and the growing number of urban climate adaptation plans provide instruments for planning (Carter et al., 2015; Dhar and Khirfan, 2017; Siders, 2017; Stults and Woodruff, 2017). Adaptation plans can reduce exposure to urban flood risk that, in a 1.5°C world, could double relative to 1976–2005 (Alfieri et al., 2017), reduce heat stress (Section 3.5.5.8), fire risk (Section 3.4.3.4) and sea-level rise (Section 3.4.5.1) (Schleussner et al., 2016).

Cities can reduce their risk exposure by considering investment in infrastructure and buildings that are more resilient to warming of 1.5°C or beyond. Where adaptation planning and urban planning generate the type of local participation that enhances capacity to cope with risks, they can be mutually supportive processes (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Chu et al., 2017; Siders, 2017; Underwood et al., 2017). Not all adaptation plans are reported as effective (Measham et al., 2011; Hetz, 2016; Woodruff and Stults, 2016; Mahlkow and Donner, 2017), especially in developing country cities (Kiunsi, 2013). Where adaptation planning further marginalises poor citizens through limited local control over establishing adaptation priorities, or the displacement of impacts onto poorer communities, justice, equity, and broad participation would need to be considered in the dimensions of successful urban risk reduction, and recognition of the political economy of adaptation (Archer, 2016; Shi et al., 2016; Ziervogel et al., 2016a, 2017; Chu et al., 2017).

4.3.3.7 Green Urban Infrastructure and Ecosystem Services

Integrating and promoting green urban infrastructure (including street trees, parks, green roofs and facades, water features) into city planning can be difficult (Leck et al., 2015) and increases urban resilience to impacts of 1.5°C warming (Table 4.2) in ways that can be more cost effective than conventional infrastructure (Culwick and Bobbins (2016) (Cartwright et al., 2013).

Table 4.2: Green urban infrastructure and benefits.

Green infrastructure	Adaptation benefits	Mitigation benefits	References
Urban trees planting, urban parks	Reduced heat island effect, psychological benefits	Less cement, reduced air-conditioning	(Demuzere et al., 2014; Mullaney et al., 2015; Soderlund and Newman, 2015; Beaudoin and Gosselin, 2016; Green et al., 2016; Lin et al., 2017)
Permeable surfaces	Water recharge	Less cement in city, some bio-sequestration, less water pumping	(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017)
Forest retention, and urban agricultural land	Flood mediation, healthy lifestyles	Air pollution reduction	(Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; White et al., 2017)
Wetland restoration,	Reduced urban flooding, Low	Some bio-sequestration, Less	(Cartwright et al., 2013; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016;

riparian buffer zones	skilled local work, Sense of place	energy spent on water treatment	Culwick and Bobbins, 2016; McPhearson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; F. Li et al., 2017)
Biodiverse urban habitat	Psychological benefits, inner-city recreation	Carbon sequestration	(Beatley, 2011; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Collas et al., 2017; F. Li et al., 2017)

Realising climate benefits from urban green infrastructure sometimes requires a city-region perspective (Wachsmuth et al., 2016). Where the urban impact on ecological systems in and beyond the city is appreciated, the potential for transformative change exists (Soderlund and Newman, 2015; Ziervogel et al., 2016a), and a locally appropriate combination of green space, ecosystem goods and services and the built environment can increase the set of urban adaptation options (Puppim de Oliveira et al., 2013).

Milan, Italy, a city with deliberate urban greening policies, planted 10,000 hectares of new forest and green areas over the last two decades (Sanesi et al., 2017). The accelerated growth of urban trees, relative to rural trees, in several regions of the world is expected to decrease tree longevity (Pretzsch et al., 2017), requiring monitoring and additional management of urban trees if their contribution to urban ecosystem based adaptation and mitigation is to be maintained in a 1.5°C world (Buckeridge, 2015; Pretzsch et al., 2017).

4.3.3.8 Sustainable Urban Water and Environmental Services

Urban water supply and wastewater treatment is energy intensive, and currently accounts for significant GHG emissions (Nair et al., 2014). Cities can integrate sustainable water resource management and the supply of water services in ways that support mitigation, adaptation and development through waste-water recycling and storm water diversion (Xue et al., 2015; Poff et al., 2016). Governance and finance challenges complicate balancing sustainable water supply and rising urban demand, particularly in low-income cities (Bettini et al., 2015; Deng and Zhao, 2015; Hill Clarvis and Engle, 2015; Lemos, 2015; Margerum and Robinson, 2015).

Urban surface sealing with impervious materials affects the volume and velocity of run-off and flooding during intense rainfall (Skougaard Kaspersen et al., 2015), but urban design in many cities now seeks to mediate run-off, encourage groundwater recharge and enhance water quality (Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017). Challenges remain for managing intense rainfall events that are reported to be increasing in frequency and intensity in some locations (Ziervogel et al., 2016b) and urban flooding is expected to increase at 1.5°C warming (Alfieri et al., 2017). This risk falls disproportionately on women and poor people in cities (Mitlin, 2005; Chu et al., 2016; Ziervogel et al., 2016b; Chant et al., 2017; Dodman et al., 2017a, b).

Nexus approaches that highlight urban areas as socio-ecological systems, can support policy coherence (Rasul and Sharma, 2016) and sustainable urban livelihoods (Biggs et al., 2015). The Water-Energy-Food (WEF) nexus is especially important to growing urban populations (Tacoli et al., 2013; Lwasa et al., 2014; Villarroel Walker et al., 2014).

4.3.4 Industrial Systems Transitions

Industry consumes about one third of global final energy and contributes, directly and indirectly, about one third of global GHG emissions (IPCC, 2014b). If global temperatures are to remain under 1.5°C, modelling indicates that industry cannot emit more than 2 $GtCO_2$ in 2050, corresponding > 70% GHG emission reduction compared to 2010 (see Figures 2.20 and 2.21). Moreover, the consequences of climate change of 1.5°C or more pose substantial challenges for industrial diversity. This section will first briefly discuss the limited literature on adaptation options for industry. Subsequently, new literature since AR5 on the feasibility of industrial mitigation options will be discussed.

Research assessing adaptation actions by industry indicates that only a small fraction of corporations have developed adaptation measures. Studies of adaptation in the private sector remain limited (Agrawala et al., 2011; Linnenluecke et al., 2015; Averchenkova et al., 2016; Bremer and Linnenluecke, 2016; Pauw et al., 2016a) and for 1.5ºC are largely absent. This knowledge gap is particularly evident for medium-sized enterprises and in low- and middle-income nations (Surminski, 2013).

Depending on the industrial sector, mitigation consistent with 1.5ºC would mean, across industries, a reduction of final energy demand by one-third, an increase of the rate of recycling of materials and the development of a circular economy in industry (Lewandowski, 2016; Linder and Williander, 2017), the substitution of materials in high-carbon products with those made up of renewable materials (e.g., wood instead of steel or cement in the construction sector, natural textile fibres instead of plastics), and a range of deep emission reduction options, including use of bio-based feedstocks, low-emission heat sources, electrification of production processes, and/or capture and storage of all CO_2 emissions by 2050 (Åhman et al., 2016). Some of the choices for mitigation options and routes for GHG-intensive industry are discrete and potentially subject to path dependency: if an industry goes one way (e.g., in keeping existing processes), it will be harder to transition to process change (e.g., electrification) (Bataille et al., 2018). In the context of rising demand for construction, an increasing share of industrial production may be based in developing countries (N. Li et al., 2017), where current efficiencies may be lower than in developed countries, and technical and institutional feasibility may differ (Ma et al., 2015).

Except for energy efficiency, costs of disruptive change associated with hydrogen- or electricity-based production, bio-based feedstocks and Carbon Dioxide Capture, (Utilisation) and Storage (CC(U)S) for trade-sensitive industrial sectors (in particular the iron and steel, petrochemical and refining industries) make policy action by individual countries challenging because of competitiveness concerns (Åhman et al., 2016; Nabernegg et al., 2017).

Table 4.3 provides an overview of applicable mitigation options for key industrial sectors.

Table 4.3: Overview of different mitigation options potentially consistent with 1.5ºC and applicable to main industrial sectors, including examples of application (Napp et al., 2014; Boulamanti and Moya, 2017; Wesseling et al., 2017).

	Iron/steel	**Cement**	**Refineries and petrochemicals**	**Chemicals**
Process and energy efficiency	Can make a difference on of between 10% and 50%, depending on the plant. Relevant but not enough for 1.5ºC			
Bio-based	Coke can be made from biomass instead of coal	Partial (only energy-related emissions)	Biomass can replace fossil feedstocks	
Circularity & substitution	More recycling and replacement by low-emission materials, including alternative chemistries for cement		Limited potential	
Electrification & hydrogen	Direct reduction with hydrogen. Heat generation through electricity	Partial (only electrified heat generation)	Electrified heat and hydrogen generation	
CCS	Possible for process emissions and energy. Reduces emissions by 80-95%, and become negative when combined with biofuel		Can be applied to energy emissions and different stacks but not on emissions of products in the use phase (e.g., gasoline)	

4.3.4.1 Energy Efficiency

Isolated efficiency implementation in energy-intensive industries is a necessary but insufficient condition for deep emission reductions (Napp et al., 2014; Aden, 2017). Various options specific to different industries are available. In general, their feasibility depends on lowering capital costs and raising awareness and expertise (Wesseling et al., 2017). General purpose technologies, such as ICT, and energy management tools can improve the prospects of energy efficiency in industry (see Section 4.4.4).

Cross-sector technologies and practices, which play a role in all industrial sectors including Small- and Medium-sized Enterprises (SMEs) and non-energy intensive industry, also offer potential for considerable energy efficiency improvements. They include motor systems (for example electric motors, variable speed drives, pumps, compressors and fans), responsible for about 10% of industrial energy consumption with an energy efficiency improvement potential of around 20–25%, worldwide (Napp et al., 2014); steam systems, responsible for about 30% of industrial energy consumption and energy saving potentials of about 10% (Hasanbeigi et al., 2014; Napp et al., 2014). Waste heat recovery from industry has substantial potential for energy efficiency and emission reduction (Forman et al., 2016). Low awareness and competition from other investments limit the feasibility of such options (Napp et al., 2014).

4.3.4.2 Substitution and Circularity

Recycling materials and developing a circular economy can be institutionally challenging as it requires advanced capabilities (Henry et al., 2006) and organisational changes (Cooper- Searle et al., 2018), but has advantages in terms of cost, health, governance and environment (Ali et al., 2017). An assessment of the impacts on energy use and environmental issues is not available, but substitution could play a large role in reducing emissions (Åhman et al., 2016) although its potential depends on the demand for material, and the turnover of for example in buildings (Haas et al., 2015). Material substitution and CO_2 storage options are under development, for example, the use of algae and renewable energy for carbon fibre production, which could become a net sink of CO_2 (Arnold et al., 2018).

4.3.4.3 Bio-Based Feedstocks

Bio-based feedstock processes could be partly seen as part of the circular materials economy (see Section above). In several sectors, bio-based feedstocks would leave the production process of materials relatively untouched, and a switch would not affect the product quality, making the option more attractive. However, energy requirements for processing bio-based feedstocks are often high, costs are also still higher, and the emissions over the full lifecycle, both upstream and downstream, could be significant (Wesseling et al., 2017). Bio-based feedstocks may put pressure on natural resources by increasing land demand, biodiversity impacts beyond bioenergy demand for electricity, transport and buildings (Slade et al., 2014), and, partly as a result, face barriers in public acceptance (Sleenhoff et al., 2015).

4.3.4.4 Electrification and Hydrogen

Electrification of manufacturing processes would constitute a significant technological challenge and a more disruptive innovation in industry than bio-based or CCS options, to get to very low or zero emissions, except potentially in steel-making (Philibert, 2017). The disruptive characteristics could potentially lead to stranded assets, and could reduce political feasibility and industry support (Åhman et al., 2016). Electrification of manufacturing would require further technological development in industry, as well as an ample supply of cost-effective low-emission electricity (Philibert, 2017).

Low-emission hydrogen can be produced either by natural gas with CCS, by electrolysis of water powered by zero-emission electricity, or potentially in the future by generation IV nuclear reactors. Feasibility of electrification and use of hydrogen in production processes or fuel cells is affected by technical development in terms of efficient hydrogen production and electrification of processes, by geophysical factors related to the availability of low-emission electricity (MacKay, 2013), by associated public perception and by economic feasibility, except in areas with ample solar and/or wind resources (Philibert, 2017; Wesseling et al., 2017).

4.3.4.5 CO_2 Capture, Utilisation and Storage in Industry

CO_2 capture in industry is generally considered more feasible than CCS in the power sector (Section 4.3.1) or from bioenergy sources (Section 4.3.7), although CCS in industry faces similar barriers. Almost all of the current full-scale (>1MtCO_2 yr^{-1}) CCS projects capture CO_2 from industrial sources, including the Sleipner project in Norway, which has been injecting CO_2 from a gas facility in an offshore saline formation since 1996 (Global CCS Institute, 2017). Compared to the power sector, retrofitting CCS on existing industrial plants would leave the production process of materials relatively untouched (Åhman et al., 2016), though significant investments and modifications still have to be made. Some industries, in particular cement, emit CO_2 as inherent process emissions and can therefore not reduce emissions to zero without CC(U)S. CO_2 stacks in some industries have a high economic and technical feasibility for CO_2 capture as the CO_2 concentration in the exhaust gases is relatively high (IPCC, 2005; Leeson et al., 2017), but others require strong modifications in the production process, limiting technical and economic feasibility, though costs remain lower than other deep GHG reduction options (Rubin et al., 2015). There are indications that the energy use in CO_2 capture through amine solvents (for solvent regeneration) can decrease by around 60%, from 5 GJ tCO_2^{-1} in 2005 to 2 GJ tCO_2^{-1} in the best-performing pilot plants (Idem et al., 2015), increasing both technical and economic potential for this option. The heterogeneity of industrial production processes might point to the need for specific institutional arrangements to incentivise industrial CCS (Mikunda et al., 2014), and may decrease institutional feasibility.

The contribution of Carbon Dioxide Utilisation (CCU) to limiting warming to 1.5°C depends on the origin of CO_2 (fossil, biogenic or atmospheric), the source of electricity for converting the CO_2 or regenerating catalysts, and the lifetime of the product. Review studies indicate that carbon dioxide utilisation in industry has a small role to play in limiting warming to 1.5°C because of the limited potential of re-using CO_2 with currently available technologies and the re-emission of CO_2 when used as a fuel (IPCC, 2005; Mac Dowell et al., 2017). However, there are new developments, in particular in CO_2 use as a feedstock for carbon-based materials that would isolate CO_2 from the atmosphere for a long time and greater availability of low-cost, low-emission electricity. The conversion of CO_2 to fuels using zero-emission electricity has a lower technical, economic and environmental feasibility than direct CO_2 capture and storage from industry (Abanades et al., 2017), although the economic prospects have improved recently (Philibert, 2017).

4.3.5 Overarching Adaptation Options Supporting Adaptation Transitions

This section assesses overarching adaptation options, which are specific solutions from which actors can choose and make decisions to reduce climate vulnerability and build resilience. We examine their feasibility in the context of transitions of energy, land and ecosystem, urban and infrastructure, and industrial systems here, and further in Section 4.5. These options can contribute to creating an enabling environment for adaptation (see Table 4.4 and Section 4.4).

4.3.5.1 Disaster Risk Management (DRM)

DRM is a process for designing, implementing and evaluating strategies, policies and measures to improve the understanding of disaster risk, and promoting improvement in disaster preparedness, response and recovery (IPCC, 2012). There is increased demand to integrate DRM and adaptation (Howes et al., 2015; Kelman et al., 2015; Serrao-Neumann et al., 2015; Archer, 2016; Rose, 2016; van der Keur et al., 2016; Kelman, 2017; Wallace, 2017) to reduce vulnerability, but institutional, technical and financial capacity challenges in frontline agencies constitute constraints (*medium evidence, high agreement)* (Eakin et al., 2015; Kita, 2017; Wallace, 2017).

4.3.5.2 Risk Sharing and Spreading

Risks associated with 1.5ºC warming (Section 3.4) have the potential to increase the demand for options that share and spread financial burdens. Formal, market-based (re)insurance spreads risk and provides a financial buffer against the impact of climate hazards (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Patel et al., 2017). As an alternative to traditional indemnity-based insurance, index-based micro-crop and livestock insurance programmes have been rolled out in regions with less developed insurance markets (Akter et al., 2016, 2017; Jensen and Barrett, 2017). There is *medium evidence* and *medium agreement* on the feasibility of insurance for adaptation, with financial, social, and institutional barriers to implementation and uptake, especially in low-income nations (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016). Social protection programmes include cash and in-kind transfers to protect poor and vulnerable households from the impact of economic shocks, natural disasters and other crises (World Bank, 2017b), and can build generic adaptive capacity and reduce vulnerability when combined with a comprehensive climate risk management approach (*medium evidence*, *medium agreement*) (Devereux, 2016; Lemos et al., 2016).

4.3.5.3 Education and Learning

Educational adaptation options motivate adaptation through building awareness (Butler et al., 2016; Myers et al., 2017), leveraging multiple knowledge systems (Pearce et al., 2015; Janif et al., 2016), developing participatory action research and social learning processes (Butler and Adamowski, 2015; Ensor and Harvey, 2015; Butler et al., 2016; Thi Hong Phuong et al., 2017; Ford et al., 2018), strengthening extension services, and building learning and knowledge sharing mechanisms through community-based platforms, international conferences and knowledge networks (Vinke-de Kruijf and Pahl-Wostl, 2016) (*medium evidence*, *high agreement*).

4.3.5.4 Population Health and Health System Adaptation Options

Until mid-century, climate change will exacerbate existing health challenges (Section 3.4.7). Enhancing current health services includes providing access to safe water and improved sanitation, enhancing access to essential services such as vaccination, and developing or strengthening integrated surveillance systems (WHO, 2015). Combining these with iterative management can facilitate effective adaptation (*medium evidence*, *high agreement)*.

4.3.5.5 Indigenous Knowledge

There is *medium evidence* and *high agreement* that Indigenous knowledge is critical for adaptation, underpinning adaptive capacity through the diversity of Indigenous agro-ecological and forest management systems, collective social memory, repository of accumulated experience, and social networks (Hiwasaki et al., 2015; Pearce et al., 2015; Mapfumo et al., 2016; Sherman et al., 2016; Ingty, 2017) (Box 4.3). It is threatened by acculturation, dispossession of land rights and land grabbing, rapid environmental changes, colonisation, and social change, increasing vulnerability to climate change, which climate policy can exacerbate if based on limited understanding of Indigenous worldviews (Thornton and Manasfi, 2010; Ford, 2012; Nakashima et al., 2012; McNamara and Prasad, 2014). Many scholars argue that recognition of Indigenous rights, governance systems and laws is central to adaptation, mitigation and sustainable development (Magni, 2017; Thornton and Comberti, 2017; Pearce, 2018).

4.3.5.6 Human Migration

Human migration, whether planned, forced or voluntary, is increasingly gaining attention as a response, particularly where climatic risks are becoming severe (Section 3.4.10.2). There is *medium evidence* and *low agreement* as to whether migration is adaptive, in relation to cost effectiveness (Grecequet et al., 2017) and scalability (Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017) concerns. Migrating can have mixed outcomes on reducing socio-economic vulnerability (Birk and Rasmussen, 2014;

Kothari, 2014; Adger et al., 2015; Betzold, 2015; Kelman, 2015; Grecequet et al., 2017; Melde et al., 2017; World Bank, 2017a, 2018b) and its feasibility is constrained by low political and legal acceptability, and inadequate institutional capacity (Betzold, 2015; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al., 2017).

4.3.5.7 Climate Services

There is *medium evidence* and *high agreement* that climate services can play a critical role in aiding adaptation decision making (Vaughan and Dessai, 2014; Wood et al., 2014; Lourenço et al., 2016; Trenberth et al., 2016; Singh et al., 2017; Vaughan et al., 2018). The higher uptake of short-term climate information such as weather advisories and daily forecasts contrast with lesser use of longer-term information such as seasonal forecasts and multi-decadal projections (Singh et al., 2017; Vaughan et al., 2018). Climate service interventions have met challenges with scaling-up due to low capacity, inadequate institutions, and difficulties in maintaining systems beyond pilot project stage (Sivakumar et al., 2014; Tall et al., 2014; Gebru et al., 2015; Singh et al., 2016b), and technical, institutional, design, financial and capacity barriers to the application of climate information for better decision-making remain (WMO, 2015; Briley et al., 2015; L. Jones et al., 2016; Lourenço et al., 2016; Snow et al., 2016; Harjanne, 2017; Singh et al., 2017; C.J. White et al., 2017).

Table 4.4: Assessment of overarching adaptation options in relation to enabling conditions. For more details, see Supplementary Material 4.B.

Option	Enabling Conditions	Examples
Disaster risk management (DRM)	Governance and institutional capacity: supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016).	Early warning systems (Anacona et al., 2015), and monitoring of dangerous lakes and surrounding slopes (including using remote sensing) offer DRM opportunities (Emmer et al., 2016; Milner et al., 2017).
Risk sharing and spreading: insurance	Institutional capacity and finance: buffers climate risk (Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017).	In 2007, the Caribbean Catastrophe Risk Insurance Facility was formed to pool risk from tropical cyclones, earthquakes, and excess rainfalls (Murphy et al., 2012; CCRIF, 2017).
Risk sharing and spreading: social protection programmes	Institutional capacity and finance: builds generic adaptive capacity and reduces social vulnerability (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017).	In sub-Saharan Africa, cash transfer programmes targeting poor communities have proven successful in smoothing household welfare and food security during droughts, strengthening community ties, and reducing debt levels (del Ninno et al., 2016; Asfaw et al., 2017; Asfaw and Davis, 2018).
Education and learning	Behavioural change and institutional capacity: social learning strengthens adaptation and affects longer-term change (Clemens et al., 2015; Ensor and Harvey, 2015; Henly-Shepard et al., 2015).	Participatory scenario planning is a process by which multiple stakeholders work together to envision future scenarios under a range of climatic conditions (Oteros-Rozas et al., 2015; Butler et al., 2016; Flynn et al., 2018).
Population health and health system	Institutional capacity: 1.5°C warming will primarily exacerbate existing health challenges (K.R. Smith et al., 2014), which can be targeted by enhancing health services.	Heat wave early warning and response systems coordinate the implementation of multiple measures in response to predicted extreme temperatures (e.g. public announcements, opening public cooling shelters, distributing information on heat stress symptoms) (Knowlton et al., 2014; Takahashi et al., 2015; Nitschke et al., 2016, 2017).
Indigenous knowledge	Institutional capacity and behavioural change: knowledge of environmental conditions helps communities detect and monitor change (Johnson et al., 2015; Mistry and Berardi, 2016; Williams et al., 2017).	Options such as integration of Indigenous knowledge into resource management systems and school curricula, are identified as potential adaptations (Cunsolo Willox et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015; Pearce et al., 2015; Chambers et al., 2017; Inamara and Thomas, 2017).

Human migration	Governance: revising and adopting migration issues in national disaster risk management policies, National Adaptation Plans and NDCs (Kuruppu and Willie, 2015; Yamamoto et al., 2017).	In dryland India, populations in rural regions already experiencing 1.5°C warming are migrating to cities (Gajjar et al., 2018) but are inadequately covered by existing policies (Bhagat, 2017).
Climate services	Technological innovation: rapid technical development (due to increased financial inputs and growing demand) is enabling quality of climate information provided (WMO, 2015; Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; Roudier et al., 2016).	Climate services are seeing wide application in sectors such as agriculture, health, disaster management, insurance (Lourenço et al., 2016; Vaughan et al., 2018) with implications for adaptation decision-making (Singh et al., 2017).

[START CROSS-CHAPTER BOX 9 HERE]

Cross-Chapter Box 9: Risks, Adaptation Interventions, and Implications for Sustainable Development and Equity Across Four Social-Ecological Systems: Arctic, Caribbean, Amazon, and Urban

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This box presents four case studies from different social-ecological systems as examples of risks of 1.5ºC warming and higher (Chapter 3); adaptation options that respond to these risks (Chapter 4); and their implications for poverty, livelihoods and sustainability (Chapter 5). It is not yet possible to generalise adaptation effectiveness across regions due to a lack of empirical studies and monitoring and evaluation of current efforts.

Arctic

The Arctic is undergoing the most rapid climate change globally (Larsen et al., 2014), warming by 1.9°C over the last 30 years (Walsh, 2014; Grosse et al., 2016). For 2°C warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher than at 1.5°C (see Sections 3.3.5 and 3.3.8), with permafrost melt, increased instances of storm surge, and extreme weather events anticipated along with later ice freeze up, earlier break up, and a longer ice free open water season (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Chadburn et al., 2017; Melvin et al., 2017). Negative impacts on health, infrastructure, and economic sectors (AMAP, 2017a, b, 2018) are projected, although the extension of the summer ocean shipping season has potential economic opportunities (Ford et al., 2015b; Dawson et al., 2016; K.Y. et al., 2018).

Communities, many with Indigenous roots, have adapted to environmental change, developing or shifting harvesting activities and patterns of travel and transitioning economic systems (Forbes et al., 2009; Wenzel, 2009; Ford et al., 2015a; Pearce et al., 2015), although emotional and psychological effects have been documented (Cunsolo Willox et al., 2012; Cunsolo and Ellis, 2018). Besides climate change (Keskitalo et al., 2011; Loring et al., 2016), economic and social conditions can constrain the capacity to adapt unless resources and cooperation are available from public and private sector actors (AMAP, 2017a, 2018)(see Box 5.3Section). In Alaska, the economic impacts of climate change on public infrastructure are significant, estimated at 5.5 billion USD to 4.2 billion USD from 2015 to 2099, with adaptation efforts halving these estimates (Melvin et al., 2017). Marginalisation, colonisation, and land dispossession provide broader underlying challenges facing many communities across the circumpolar north in adapting to change (Ford et al., 2015a; Sejersen, 2015) (see Section 4.3.5).

Adaptation opportunities include alterations to building codes and infrastructure design, disaster risk management, and surveillance (Ford et al., 2014a; AMAP, 2017a, b; Labbé et al., 2017). Most adaptation initiatives are currently occurring at local levels in response to both observed and projected environmental changes as well as social and economic stresses (Ford et al., 2015a). In a recent study of Canada, most adaptations were found to be in the planning stages (Labbé et al., 2017). Studies have suggested that a number of the adaptation actions are not sustainable, lack evaluation frameworks, and hold potential for maladaptation (Loboda, 2014; Ford et al., 2015a; Larsson et al., 2016). Utilising Indigenous and local knowledge and stakeholder engagement can aid the development of adaptation policies and broader sustainable development, along with more proactive and regionally coherent adaptation plans and actions, and regional cooperation (e.g. through the Arctic Council) (Larsson et al., 2016; AMAP, 2017a; Melvin et al., 2017; Forbis Jr and Hayhoe, 2018) (see Section 4.3.5).

Caribbean SIDS and Territories

Extreme weather, linked to tropical storms and hurricanes, represent one of the largest risks facing Caribbean island nations (Section 3.4.5.3). Non-economic damages include detrimental health impacts, forced displacement and destruction of cultural heritages. Projections of increased frequency of the most intense storms at 1.5ºC and higher warming levels (Wehner et al., 2018; Section 3.3.6; Box 3.5) are a significant cause for concern, making adaptation a matter of survival (Mycoo, 2017).

Despite a shared vulnerability arising from commonalities in location, circumstance and size (Bishop and Payne, 2012; Nurse et al., 2014), adaptation approaches are nuanced by differences in climate governance, affecting vulnerability and adaptive capacity (see Section 4.4.1). Three cases exemplify differences in disaster risk management.

Cuba: Together with a robust physical infrastructure and human resource base (Kirk, 2017), Cuba has implemented an effective civil defence system for emergency preparedness and disaster response, centred around community mobilisation and preparedness (Kirk, 2017). Legislation to manage disasters, an efficient and robust early warning system, emergency stockpiles, adequate shelter system and continuous training and education of the population help create a ‘culture of risk’ (Isayama and Ono, 2015; Lizarralde et al., 2015) which reduces vulnerability to extreme events (Pichler and Striessnig, 2013). Cuba’s infrastructure is still susceptible to devastation, as seen in the aftermath of the 2017 hurricane season.

United Kingdom Outer Territories (UKOT): All UKOT have developed National Disaster Preparedness Plans (PAHO/WHO, 2016) and are part of the Caribbean Disaster Risk Management Program which aims to improve disaster risk management within the health sector. Different vulnerability levels across the UKOT (Lam et al., 2015) indicate the benefits of greater regional cooperation and capacity-building, not only within UKOT, but throughout the Caribbean (Forster et al., 2011). While sovereign states in the region can directly access climate funds and international support, Dependent Territories are reliant on their controlling states (Bishop and Payne, 2012). There tends to be low-scale management for environmental issues in UKOT, which increases UKOT’s vulnerability. Institutional limitations, lack of human and financial resources, and limited long-term planning are identified as barriers to adaptation (Forster et al., 2011).

Jamaica: Disaster management is coordinated through a hierarchy of national, parish and community disaster committees under the leadership of the Office of Disaster Preparedness and Emergency Management (ODPEM). ODPEM coordinates disaster preparedness and risk reduction efforts among key state and non-state agencies (Grove, 2013). A National Disaster Committee provides technical and policy oversight to the ODPEM and is comprised of representatives from multiple stakeholders (Osei, 2007). Most initiatives are primarily funded through a mix of multi-lateral and bi-lateral loan and grant funding focusing on strengthening technical and institutional capacities of state and research-based institutions and supporting integration of climate change considerations into national and sectoral development plans (Robinson, 2017).

To improve climate change governance in the region, Pittman et al 2015 suggest incorporating holistic and integrated management systems, improving flexibility in collaborative processes, implementing monitoring programs, and increasing the capacity of local authorities. Implementation of the 2030 Sustainable Development Agenda and the Sustainable Development Goals (SDGs) can contribute to addressing the risks related with extreme events (Box 5.3).

The Amazon
Terrestrial forests, such as the Amazon, are sensitive to changes in the climate, particularly drought (Laurance and Williamson, 2001) which might intensify through the 21st century (Marengo and Espinoza, 2016) (Section 3.5.5.6).

The poorest communities in the region face substantial risks with climate change, and barriers and limits to adaptive capacity (Maru et al., 2014; Pinho et al., 2014, 2015; Brondízio et al., 2016). The Amazon is considered a hotspot with interconnections between increasing temperature, decreased precipitation and hydrological flow (Betts et al., 2018) (Sections 3.3.2.2, 3.3.3.2 and 3.3.5), low levels of socioeconomic development (Pinho et al., 2014), and high levels of climate vulnerability (Darela et al., 2016). Limiting temperature warming to 1.5°C could increase food and water security in the region compared to 2°C (Betts et al., 2018), reduce the impact on poor people and sustainable development, and make adaptation easier (O'Neill et al., 2017) particularly in the Amazon (Bathiany et al., 2018) (Section 5.2.2).

Climate policy in many Amazonian nations has focused on forests as carbon sinks (Soares-Filho et al., 2010). In 2009, the Brazilian National Policy on Climate Change acknowledged adaptation as a concern and the government sought to mainstream adaptation into public administration. Brazil's National Adaptation Plan sets guidelines for sectoral adaptation measures, primarily by developing capacity building, plans, assessments and tools to support adaptive decision making. Adaptation is increasingly being presented as having mitigation co-benefits in the Brazilian Amazon (Gregorio et al., 2016), especially within ecosystem-based adaptation (Locatelli et al., 2011). In Peru's Framework Law for Climate Change, every governmental sector will consider climatic conditions as potential risks and/or opportunities to promote economic development and to plan adaptation.

Drought and flood policies have had limited effectiveness in reducing vulnerability (Marengo et al., 2013). In the absence of effective adaptation, achieving the SDGs will be challenging, mainly in poverty, health, water and sanitation, inequality and gender equality (Section 5.2.3).

Urban systems
Around 360 million people reside in urban coastal areas where precipitation variability is exposing inadequacies of urban infrastructure and governance, with the poor especially vulnerable (Reckien et al., 2017)(Cross-Chapter Box 13 in Chapter 5). Urban systems have seen growing adaptation action (Revi et al., 2014b; Araos et al., 2016b; Amundsen et al., 2018). Developing cities spend more on health and agriculture-related adaptation options while developed cities spend more on energy and water (Georgeson et al., 2016). Current adaptation activities are lagging in emerging economies which are major centres of population growth facing complex interrelated pressures on investment in health, housing and education (Georgeson et al., 2016; Reckien et al., 2017).

New York: Adaptation plans are undertaken across government levels, sectors and departments (NYC Parks, 2010; Vision 2020 Project Team, 2011; The City of New York, 2013), and have been advanced by an expert science panel that is obligated by local city law to provide regular updates on policy relevant climate science (NPCC, 2015). Federal initiatives include 2013's Rebuild By Design competition to promote resilience through infrastructural projects (HUD, 2013). In 2013 the Mayor's office, in response to Hurricane Sandy, published the city's adaptation strategy (The City of New York, 2013). In 2015, the OneNYC Plan for a Strong and Just City (OneNYC Team, 2015) laid out a strategy for urban planning through a justice and equity lens. In 2017, new climate resiliency guidelines proposed that new construction must include sea level rise projections into planning and development (The City of New York, 2017). Although this attention to climate-resilient development may help reduce income inequality, its full effect could be constrained, if a policy focus on resilience obscures analysis of income redistribution for the poor (Fainstein, 2018).

Kampala: Kampala Capital City Authority (KCCA) has the statutory responsibility for managing the city. The Kampala Climate Change Action Strategy (KCCAS) is responding to climatic impacts of elevated temperature and more intense, erratic rain. KCCAS has considered multi-scale and temporal aspects of response (Chelleri et al., 2015; Douglas, 2017; Fraser et al., 2017), strengthened community adaptation (Lwasa, 2010; Dobson, 2017), responded to differential adaptive capacities (Waters and Adger, 2017) and believes in participatory processes and bridging of citywide linkages (KCCA, 2016). Analysis of the implications of uniquely adapted local solutions (e.g., motorcycle taxis) suggests sustainability can be enhanced when planning recognises the need to adapt to uniquely local solutions (Evans et al., 2018).

Rotterdam: The Rotterdam Climate Initiative (RCI) was launched to reduce Greenhouse Gas (GHG) emissions and climate-proof Rotterdam (RCI, 2017). Rotterdam has an integrated adaptation strategy, built on flood management, accessibility, adaptive building, urban water systems and urban climate, defined through Rotterdam Climate Proof and Rotterdam Climate Change Adaptation Strategy (RCI, 2008, 2013). Governance mechanisms that enabled integration of flood risk management plans with other policies, citizen participation, institutional eco-innovation, and focussing on green infrastructure (Albers et al., 2015; Dircke and Molenaar, 2015; de Boer et al., 2016a; Huang-Lachmann and Lovett, 2016) have contributed to effective adaptation (Ward et al., 2013). Entrenched institutional characteristics constrain the response framework (Francesch-Huidobro et al., 2017) but emerging evidence suggests that new governance arrangements and structures can potentially overcome these barriers in Rotterdam (Hölscher et al., 2018).

[END CROSS-CHAPTER BOX 9 HERE]

4.3.6 Short Lived Climate Forcers

The main Short-Lived Climate Forcer (SLCF) emissions that cause warming are methane (CH_4), other precursors of tropospheric ozone (i.e., carbon monoxide (CO), Non-Methane Volatile Organic Compounds (NMVOC)), black carbon (BC) and hydrofluorocarbons (HFCs) (Myhre et al., 2013). SLCFs also include emissions that lead to cooling, such as sulphur dioxide (SO_2) and organic carbon (OC). Nitrogen oxides (NOx) can have both warming and cooling effects, by affecting ozone (O_3) and CH_4, depending on timescale and location (Myhre et al., 2013).

Cross-Chapter Box 2 in Chapter 1 provides a discussion of role of SLCFs in comparison to long-lived GHGs. Chapter 2 shows that 1.5°C-consistent pathways require stringent reductions in CO_2 and CH_4, and that non-CO_2 climate forcers reduce carbon budgets by ~2200 $GtCO_2$ per degree of warming attributed to them (see Chapter 2 Annex).

Reducing non-CO_2 emissions is part of most mitigation pathways (IPCC, 2014c). All current GHG emissions and other forcing agents affect the rate and magnitude of climate change over the next few decades, while long-term warming is mainly driven by CO_2 emissions. CO_2 emissions result in a virtually permanent warming, while temperature change from SLCFs disappears within decades after emissions of SLCFs are ceased. Any scenario that fails to reduce CO_2 emissions to net zero would not limit global warming, even if SLCFs are reduced, due to accumulating CO_2-induced warming that overwhelms SLCFs' mitigation benefits in a couple of decades (Shindell et al., 2012; Schmale et al., 2014) and see Section 2.3.3.1).

Mitigation options for warming SLCFs often overlap with other mitigation options, especially since many warming SLCFs are co-emitted with CO_2. SLCFs are generally mitigated in 1.5°C- or 2°C-consistent pathways as an integral part of an overall mitigation strategy (Chapter 2). For example, section 2.3 indicates that most very low-emissions pathways include a transition away from the use of coal and natural gas in the energy sector and oil in transportation, which coincides with emission reduction strategies related to methane from the fossil fuel sector and BC from the transportation sector. Much SLCF emission reduction aims at BC-rich sectors and considers the impacts of several co-emitted SLCFs (Bond et al., 2013; Sand et al., 2015; Stohl et al., 2015). However, it is uncertain whether such strategies would lead to additional long-term climate benefits compared to BC emissions reductions achieved through CO_2 mitigation and associated co-control on BC-rich sectors in 1.5°C and 2°C pathways (Rogelj et al., 2014).

Some studies have evaluated the focus on SLCFs in mitigation strategies and point towards trade-offs between short-term SLCF benefits and lock in of long-term CO_2 warming (Smith and Mizrahi, 2013; Pierrehumbert, 2014). Reducing fossil fuel combustion will reduce aerosols levels, and thereby cause warming from removal of cooling effects (Myhre et al., 2013; Xu and Ramanathan, 2017; Samset et al., 2018). Recent studies have also found lower temperature effects of BC than what can be expected from the direct radiative forcing alone, thus questioning the effectiveness of targeted BC mitigation for climate change mitigation (Myhre et al., 2013; Baker et al., 2015; Stjern et al., 2017; Samset et al., 2018).

Table 4.5 provides an overview of three warming SLCFs and their emission sources, with examples of options for emission reductions and associated co-benefits.

Table 4.5: Overview of main characteristics of three warming Short-Lived Climate Forcers (SLCFs) (core information based on (Pierrehumbert, 2014) and (Schmale et al., 2014); rest of the details as referenced).

SLCF compound	**Atmospheric lifetime**	**Annual global emission**	**Main anthropogenic emission sources**	**Examples of options to reduce emissions consistent with 1.5°C**	**Examples of co-benefits based on** (Haines et al., 2017) **unless specified otherwise**
Methane	On the order of 10 years	0.3 $GtCH_4$ (2010) (Pierrehumbert, 2014)	Fossil fuel extraction and transportation Land-use change Livestock and rice cultivation Waste and wastewater	Managing manure from livestock Intermittent irrigation of rice Capture and usage of fugitive methane Dietary change For more: see Sections 4.3.2 and 4.3.3.	Reduction of tropospheric ozone (Shindell et al., 2017a) Health benefits of dietary changes Increased crop yields Improved access to drinking water
HFCs	Months to decades, depending on the gas	0.35 $GtCO_2$-eq (2010) (Velders et al., 2015)	Air conditioning Refrigeration Construction material	Alternatives to HFCs in air-conditioning and refrigeration applications	Greater energy efficiency (Mota-Babiloni et al., 2017)
Black carbon	Days	~7 Mt (2010) (Klimont et al., 2017)	Incomplete combustion of fossil fuels or biomass in vehicles (esp. diesel), cook stoves or kerosene lamps Field and biomass burning	Fewer and cleaner vehicles Reducing agricultural biomass burning Cleaner cook stoves, gas-based or electric cooking Replacing brick and coke ovens Solar lamps For more see Section 4.3.4	Health benefits of better air quality Increased education opportunities Reduced coal consumption for modern brick kilns Reduced deforestation

A wide range of options to reduce SLCF emissions was extensively discussed in AR5 (IPCC, 2014b). Fossil fuel and waste sector methane mitigation options have high cost-effectiveness, producing a net profit over a few years, considering market costs only. Moreover, reducing roughly one-third to one-half of all human-caused emissions has societal benefits greater than mitigation costs when considering environmental impacts only (UNEP, 2011; Höglund-Isaksson, 2012; IEA, 2017b; Shindell et al., 2017a). Since AR5, new options for methane, such as those related to shale gas, have been included in mitigation portfolios (e.g., Shindell et al. 2017b).

Reducing BC emissions and co-emissions has sustainable development co-benefits, especially around human health (Stohl et al., 2015; Haines et al., 2017; Aakre et al., 2018), avoiding premature deaths and increasing crop yields (Scovronick et al., 2015; Peng et al., 2016). Additional benefits include lower likelihood of non-linear climate changes and feedbacks (Shindell et al., 2017a) and temporarily slowing down the rate of sea level rise (Hu et al., 2013). Interventions to reduce BC offer tangible local air quality benefits, increasing the likelihood of local public support (Eliasson, 2014; Venkataraman et al., 2016) (see Section 5.4.1.2). Limited interagency co-ordination, poor science-policy interactions (Zusman et al., 2015), and weak policy and absence of inspections and enforcement (Kholod and Evans, 2016) are among barriers that reduce the institutional feasibility of options to reduce vehicle-induced BC emissions. A case study for India shows that switching from biomass cook stoves to cleaner gas stoves (based on liquefied petroleum gas or natural gas) or to electric cooking stoves is technically and economically feasible in most areas, but faces barriers in user preferences, costs and the organisation of supply chains (Jeuland et al., 2015). Similar feasibility considerations emerge in switching in lighting from kerosene wick lamps to solar lanterns, from current low-efficiency brick kilns and coke ovens to cleaner production technologies; and from field burning of crop residues to agricultural practices using deep-sowing and mulching technologies (Williams et al., 2011; Wong, 2012).

The radiative forcing from HFCs are currently small but have been growing rapidly (Myhre et al., 2013). The Kigali amendment (from 2016) to the Montreal Protocol set out a global accord for phasing out these compounds (Höglund-Isaksson et al., 2017). HFC mitigation options include alternatives with reduced warming effects, ideally combined with improved energy efficiency so as to simultaneously reduce CO_2 and co-emissions (Shah et al., 2015). Costs for most of HFC's mitigation potential are estimated to be below USD_{2010} 60 tCO_2-eq^{-1}, and the remainder below roughly double that number (Höglund-Isaksson et al., 2017).

Reductions in SLCFs can provide large benefits towards sustainable development, beneficial for social, institutional and economic feasibility. Strategies that reduce SLCFs can provide benefits that include improved air quality (for example (Anenberg et al., 2012)) and crop yields (for example (Shindell et al., 2012)), energy access, gender equality and poverty eradication (for example (Shindell et al., 2012; Haines et al., 2017)). Institutional feasibility can be negatively affected by an information deficit, with the absence of international frameworks for integrating SLCFs into emissions accounting and reporting mechanisms being a barrier for policy-making to address SLCF emissions (Venkataraman et al., 2016). The incentives for reducing SLCFs are particularly strong for small groups of countries, and such a collaboration could increase feasibility and effectiveness of SLCF mitigation options (Aakre et al., 2018).

4.3.7 Carbon Dioxide Removal (CDR)

CDR methods refer to a set of techniques for removing CO_2 from the atmosphere. In the context of 1.5°C-consistent pathways (Chapter 2), they serve to offset residual emissions that take longer to abate or to compensate for emissions occurring after running out of the 1.5°C carbon budget. See Cross-Chapter Box 7 in Chapter 3 for a synthesis of land-based CDR options. Cross-cutting issues and uncertainties are summarised in Table 4.6.

4.3.7.1 Bioenergy with carbon capture and storage (BECCS)

BECCS has been assessed in previous IPCC reports (IPCC, 2005; P. Smith et al., 2014; Minx et al., 2017) and has been incorporated into integrated assessment models (Clarke et al., 2014). In the meantime, 1.5°C pathways without BECCS have emerged (Bauer et al., 2018; Grübler, 2018; Mousavi and Blesl, 2018; van Vuuren et al., 2018). Still, models indicate that 3.7–8 $GtCO_2$ yr^{-1} (interquartile range) and 14 $GtCO_2$ yr^{-1} (median) would be removed by BECCS by 2050 and 2100, respectively, with some models starting BECCS in 2030 already (Section 2.3.4). BECCS is constrained by sustainable bioenergy potentials (Sections 4.3.1.2, 5.4.3 and Cross-Chapter Box 6 in Chapter 3), and availability of safe storage for CO_2 (Section 4.3.1.6). Literature estimates for BECCS mitigation potentials in 2050 range from 1-85 $GtCO_2$[4]. Fuss et al. (2018) narrow this range to 0.5–5 $GtCO_2$ yr^{-1} (*medium agreement, high evidence*) (Figure 4.3), thus falling below

[4] FOOTNOTE: As more bottom-up literature exists on bioenergy potentials, this exercise explored the bioenergy literature and converted those estimates to BECCS potential with 1EJ of bioenergy yielding 0.02–0.05 $GtCO_2$ emission reduction. For the bottom-up literature references for the potentials range, please refer to Supplementary Material C Table 1.

the upper end of 1.5°C pathways. This is, among other things, related to sustainability concerns (Boysen et al., 2017; Heck et al., 2018; Henry et al., 2018).

Assessing BECCS deployment in 2°C pathways (of about 12 $GtCO_2$-eq yr^{-1}, here considered as a lower deployment limit for 1.5°C, Smith et al. (2016b) estimate a land-use intensity of 0.3–0.5 ha tCO_2-eq^{-1} yr^{-1} using forest residues, 0.16 ha CO_2-eq^{-1} yr^{-1} for agricultural residues, and 0.03–0.1 ha tCO_2-eq^{-1} yr^{-1} for purpose-grown energy crops. The average amount of BECCS in these pathways requires 25–46% of arable and permanent crop area in 2100. Land area estimates differ in scale and are not necessarily a good indicator of competition with, e.g., food production, because requiring a smaller land area for the same potential could indicate that high-productivity agricultural land is used . In general, the literature shows *low agreement* on the availability of land (Fritz et al., 2011); see (Erb et al., 2016b) for recent advances. Productivity, food production and competition with other ecosystem services and land use by local communities are important factors for the design of regulation. These potentials and trade-offs are not homogenously distributed across regions. However, (Robledo-Abad et al., 2017) find that regions with higher potentials are understudied, given their potential contribution. Researchers have expressed the need to complement global assessments with regional, geographically explicit bottom-up studies of biomass potentials and socio-economic impacts (e.g., de Wit and Faaij 2010; Kraxner et al., 2014; Baik et al., 2018).

Energy production, land and water footprints show wide ranges in bottom-up assessments due to differences in technology, feedstock and other parameters (–1–150 EJ yr^{-1} of energy, 109–990 Mha, 6–79 MtN, 218–4758 km^3 yr^{-1} of water per $GtCO_2$ yr^{-1} (Smith and Torn, 2013; Smith et al., 2016b; Fajardy and Mac Dowell, 2017) and are not comparable to IAM pathways which consider system effects (Bauer et al., 2018). Global impacts on nutrients and albedo are difficult to quantify (Smith et al., 2016b). BECCS competes with other land-based CDR and mitigation measures for resources (Chapter 2).

There is uncertainty about the feasibility of timely upscaling. CCS (see Section 4.3.1) is largely absent from the nationally determined contributions (Spencer et al., 2015) and lowly ranked in investment priorities (Fridahl, 2017). Although there are dozens of small-scale BECCS demonstrations (Kemper, 2015) and a full scale project capturing 1 $MtCO_2$ exists (Finley, 2014)**,** this is well below the numbers associated with 1.5°C or 2°C-compatible pathways (IEA, 2016a; Peters et al., 2017). Although the majority of BECCS cost estimates are below 200 USD tCO_2^{-1} (Figure 4.3), estimates vary widely. Economic incentives for ramping up large CCS or BECCS infrastructure are weak (Bhave et al., 2017). The 2050 average investment costs for such a BECCS infrastructure for bio-electricity and biofuels are estimated at 138 and 123 billion USD yr^{-1}, respectively (Smith et al., 2016b).

BECCS deployment is further constrained by bioenergy's carbon accounting, land, water and nutrient requirements (Section 4.3.1), its compatibility with other policy goals and limited public acceptance of both bioenergy and CCS (Section 4.3.1). Current pathways are believed to have inadequate assumptions on the development of societal support and governance structures (Vaughan and Gough, 2016).
However, removing BECCS and CCS from the portfolio of available options significantly raises mitigation costs (Kriegler et al., 2013) (Bauer et al., 2018).

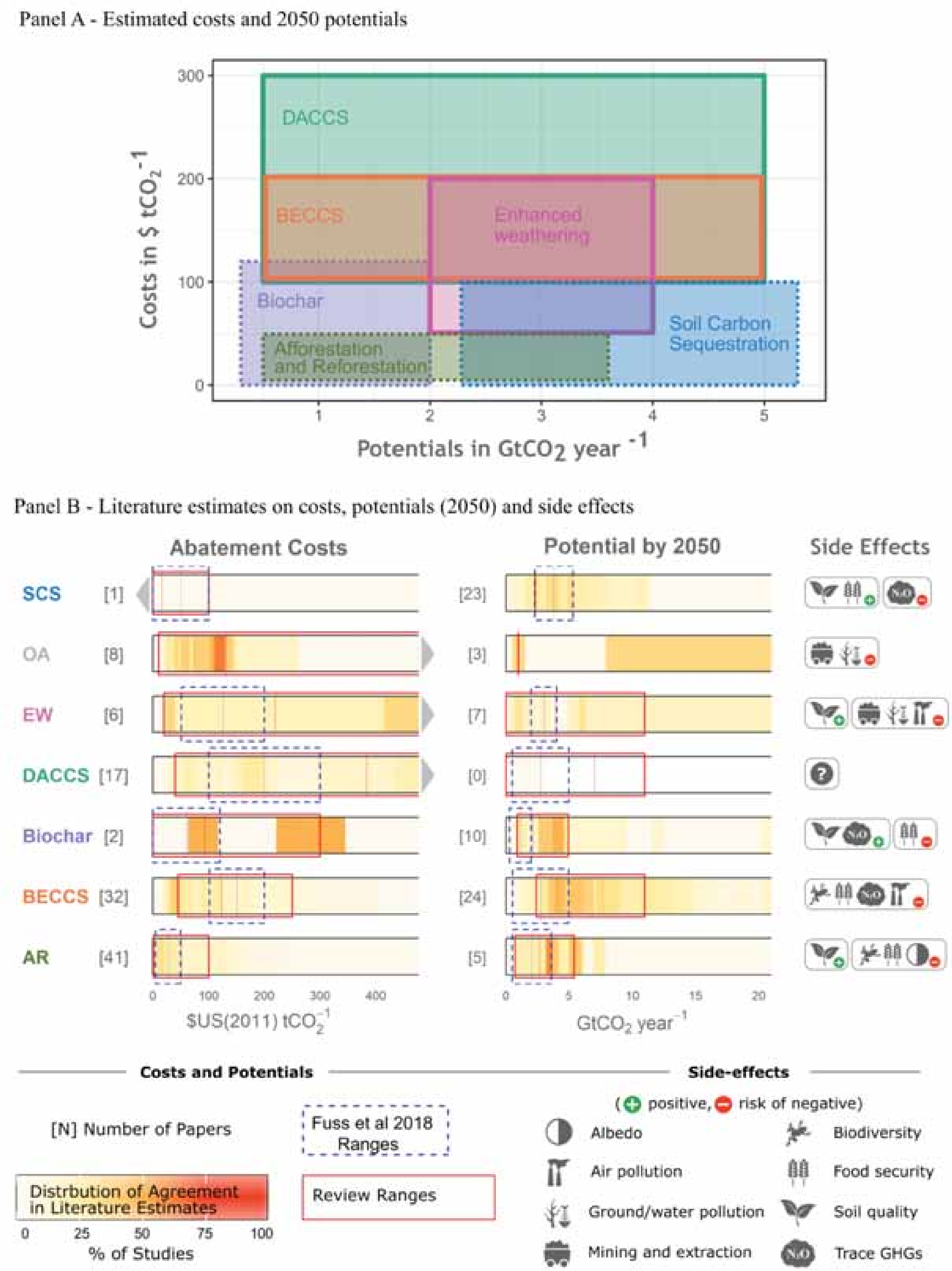

Figure 4.2: Evidence on Carbon Dioxide Removal (CDR) abatement costs, 2050 deployment potentials, and key side effects. Panel A presents estimates based on a systematic review of the bottom up literature (Fuss et al., 2018), corresponding to dashed blue boxes in Panel B. Dashed lines represent saturation limits for the corresponding technology. Panel B shows the percentage of papers at a given cost or potential estimate. Reference year for all potential estimates is 2050, while all cost estimates preceding 2050 have been

included (as early as 2030, older estimates are excluded if they lack a base year and thus cannot be made comparable). Ranges have been trimmed to show detail (see Fuss et al., 2018) for the full range). Costs refer only to abatement costs. Icons for side-effects are allocated only if a critical mass of papers corroborates their occurrence

Notes: For references please see Supplementary Material C, Table 1. Direct Air Carbon Dioxide Capture and Storage (DACCS) is theoretically only constrained by geological storage capacity, estimates presented are considering upscaling and cost challenges. BECCS potential estimates are based on bioenergy estimates in the literature (EJ yr^{-1}), converted to GtCO$_2$ following footnote 3. Potentials cannot be added up, as CDR options would compete for resources (e.g., land). SCS - Soil Carbon Sequestration; OA - Ocean Alkalinisation; EW- Enhanced Weathering; DACCS - Direct Air Carbon Dioxide Capture and Storage; BECCS - Bioenergy with Carbon Capture and Storage; AR - Afforestation

4.3.7.2 Afforestation and Reforestation (AR)

Afforestation implies planting trees on land not forested for a long time (e.g., over the last 50 years in the context of the Kyoto Protocol), while reforestation implies re-establishment of forest formations after a temporary condition with less than 10% canopy cover due to human-induced or natural perturbations. Houghton et al. (2015) estimate about 500 Mha could be available for the re-establishment of forests on lands previously forested, but not currently used productively. This could sequester at least 3.7 GtCO$_2$ yr^{-1} for decades. The full literature range gives 2050 potentials of 1–7 GtCO$_2$ yr^{-1} (*low evidence, medium agreement*), narrowed down to 0.5–3.6 GtCO$_2$ yr^{-1} based on a number of constraints (Fuss et al., 2018). Abatement costs are estimated to be low compared to other CDR options, 5–50 USD tCO$_2$-eq^{-1} (*robust evidence, high agreement*). Yet, realising such large potentials comes at higher land and water footprints than BECCS, although there would be a positive impact on nutrients, and the energy requirement would be negligible (Smith et al., 2016b; Cross-Chapter Box 7 in Chapter 3). The 2030 estimate by Griscom et al. (2017) is up to 17.9 GtCO$_2$ yr^{-1} for reforestation with significant co-benefits (Cross-Chapter Box 7 in Chapter 3).

Biogenic storage is not as permanent as emission reductions of geological storage. In addition, forest sinks saturate, a process which typically occurs in decades to centuries compared to the thousands of years of residence time of CO$_2$ stored geologically (Smith et al., 2016a) and is subject to disturbances that can be exacerbated by climate change (e.g. drought, forest fires and pests) (Seidl et al., 2017). Handling this requires careful forest management. There is much practical experience with AR, facilitating upscaling but with two caveats: AR potentials are heterogeneously distributed (Bala et al., 2007), partly because the planting of less reflective forests results in higher net-absorbed radiation and localised surface warming in higher latitudes (Bright et al., 2015; Jones et al., 2015), and forest governance structures and monitoring capacities can be bottlenecks and are usually not considered in models (Wang et al., 2016; Wehkamp et al., 2018b). There is *medium agreement* on the positive impacts of AR on ecosystems and biodiversity due to different forms of afforestation discussed in the literature: afforestation of grassland ecosystems or diversified agricultural landscapes with monocultures or invasive alien species can have significant negative impacts on biodiversity, water resources, etc. (P. Smith et al., 2014), while forest ecosystem restoration (forestry and agroforestry) with native species have positive social and environmental impacts (Cunningham et al., 2015; Locatelli et al., 2015; Paul et al., 2016); See Section 4.3.2).

Synergies with other policy goals are possible (see also Section 4.5.4); for example land spared by diet shifts could be afforested (Röös et al., 2017) or used for energy crops (Grübler, 2018). Such land-sparing strategies could also benefit other land-based CDR options.

4.3.7.3 Soil Carbon Sequestration and Biochar

At local scales there is *robust evidence* that Soil Carbon Sequestration (SCS, e.g., agroforestry, De Stefano and Jacobson, 2018), restoration of degraded land (Griscom et al., 2017), or conservation agriculture management practices (Aguilera et al., 2013; Poeplau and Don, 2015; Vicente-Vicente et al., 2016) have co-benefits in agriculture and that many measures are cost-effective even without supportive climate policy.

Evidence at global scale for potentials and especially costs is much lower. The literature spans cost ranges of –40–100 USD tCO_2^{-1} (negative costs relating to the multiple co-benefits of SCS, such as increased productivity and resilience of soils (P. Smith et al., 2014) and 2050 potentials are estimated between 1–11 $GtCO_2$ yr^{-1}, narrowed down to 2–5 $GtCO_2$ yr^{-1} considering that studies above 5 $GtCO_2$ yr^{-1} often do not apply constraints, while estimates lower than 2 $GtCO_2$ yr^{-1} mostly focus on single practices (Fuss et al., 2018).

SCS has negligible water and energy requirements (Smith, 2016), affects nutrients and food security favourably (*high agreement, robust evidence*) and can be applied without changing current land use thus making it socially more acceptable than CDR options with a high land footprint. However, soil sinks saturate after 10–100 years, depending on the SCS option, soil type and climate zone (Smith, 2016).

Biochar is formed by recalcitrant (i.e., very stable) organic carbon obtained from pyrolysis which applied to soil can increase soil carbon sequestration leading to improved soil fertility properties.[5] Looking at the full literature range, the global potential in 2050 lies between 1–35 Gt CO_2 yr^{-1} (*low agreement, low evidence*), but considering limitations in biomass availability and uncertainties due to a lack of large-scale trials of biochar application to agricultural soils under field conditions, Fuss et al. (2018) lower the 2050 range to 0.3–2 $GtCO_2$ yr^{-1}. This potential is below previous estimates (e.g., Woolf et al., 2010), which additionally consider the displacement of fossil fuels through biochar. Permanence depends on soil type and biochar production temperatures, varying between a few decades and several centuries (Fang et al., 2014). Costs are 30– 120 USD tCO_2^{-1} (*medium agreement, medium evidence*) (McCarl et al., 2009; McGlashan et al., 2012; McLaren, 2012; Smith, 2016).

Water requirements are low and at full theoretical deployment, up to 65 EJ yr^{-1} of energy could be generated as a side product (Smith, 2016). Positive side effects include a favourable effect on nutrients and reduced N_2O emissions(Cayuela et al., 2014; Kammann et al., 2017). However, 40–260 Mha are needed to grow the biomass for biochar for implementation at 0.3 $GtCO_2$-eq yr^{-1} (Smith, 2016), even though it is also possible to use residues (e.g., Windeatt et al., 2014). Biochar is further constrained by the maximum safe holding capacity of soils (Lenton, 2010) and the labile nature of carbon sequestrated in plants and soil at higher temperatures (Wang et al., 2013).

4.3.7.4 Enhanced Weathering (EW) and Ocean Alkalinisation

Weathering is the natural process of rock decomposition via chemical and physical processes in which CO_2 is spontaneously consumed and converted to solid or dissolved alkaline bicarbonates and/or carbonates (IPCC 2005). The process is controlled by temperature, reactive surface area, interactions with biota and, in particular, water solution composition. CDR can be achieved by accelerating mineral weathering through the distribution of ground-up rock material over land (Hartmann and Kempe, 2008; Wilson et al., 2009; Köhler et al., 2010; Renforth, 2012; ten Berge et al., 2012; Manning and Renforth, 2013; Taylor et al., 2016), shorelines (Hangx and Spiers, 2009; Montserrat et al., 2017) or the open ocean (House et al., 2007; Harvey, 2008; Köhler et al., 2013; Hauck et al., 2016). Ocean alkalinisation adds alkalinity to marine areas to locally increase the CO_2 buffering capacity of the ocean (González and Ilyina, 2016; Renforth and Henderson, 2017).

In the case of land application of ground minerals, the estimated CDR potential range is 0.72–95 $GtCO_2$ yr^{-1} (Hartmann and Kempe, 2008; Köhler et al., 2010; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018) *(low evidence, low agreement*). Marine application of ground minerals is limited by feasible rates of mineral extraction, grinding and delivery, with estimates of 1–6 $GtCO_2$ yr^{-1} (Köhler et al., 2013; Hauck et al., 2016; Renforth and Henderson, 2017) (*low evidence, low agreement*). Agreement is low due to a variety of assumptions and unknown parameter ranges in the applied modelling procedures that would need to be verified by field experiments (Fuss et al., 2018). As with other CDR options, scaling and maturity are

[5] FOOTNOTE: Other pyrolysis products that can achieve net CO_2 removals are bio-oil (pumped into geological storages) and permanent-pyrogas (capture and storage of CO_2 from gas combustion) (Werner et al., 2018)

challenges, with deployment at scale potentially requiring decades (NRC, 2015a), considerable costs in transport and disposal (Hangx and Spiers, 2009; Strefler et al., 2018) and mining (NRC, 2015a; Strefler et al., 2018)[6].

Site-specific cost estimates vary depending on the chosen technology for rock grinding – an energy-intensive process (Köhler et al., 2013; Hauck et al., 2016) – material transport and rock source (Renforth, 2012; Hartmann et al., 2013), ranging from 15–40 USD tCO_2^{-1} to 3,460 USD tCO_2^{-1} (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Taylor et al., 2016, *limited evidence, low agreement*; Figure 4.2). The evidence base for costs of ocean alkalinisation and marine enhanced weathering is sparser than the land applications. The ocean alkalinisation potential is assessed to be 0.1–10 $GtCO_2$ yr^{-1} with costs of 14– >500 USD tCO_2^{-1} (Renforth and Henderson, 2017).

The main side effects of terrestrial EW are an increase in water pH (Taylor et al., 2016), the release of heavy metals like Ni and Cr, and plant nutrients like K, Ca, Mg, P and Si (Hartmann et al., 2013), and changes in hydrological soil properties. Respirable particle sizes, though resulting in higher potentials, can have impacts on health (Schuiling and Krijgsman, 2006; Taylor et al., 2016); utilisation of wave-assisted decomposition through deployment on coasts could avert the need for fine grinding (Hangx and Spiers, 2009; Schuiling and de Boer, 2010). Side effects of marine EW and ocean alkalinisation are the potential release of heavy metals like Ni and Cr (Montserrat et al., 2017). Increasing ocean alkalinity helps counter ocean acidification (Albright et al., 2016; Feng et al., 2016). Ocean alkalinisation could affect ocean biogeochemical functioning (González and Ilyina, 2016). A further caveat of relates to saturation state and the potential to trigger spontaneous carbonate precipitation.[7] While the geochemical potential to remove and store CO_2 is quite large, *limited evidence* on the preceding topics makes it difficult to assess the true capacity, net benefits and desirability of EW and ocean alkalinity addition in the context of CDR.

4.3.7.5 Direct Air Carbon Dioxide Capture and Storage (DACCS)

Capturing CO_2 from ambient air through chemical processes with subsequent storage of the CO_2 in geological formations is independent of source and timing of emissions, and can avoid competition for land. Yet, this is also the main challenge: while the theoretical potential for DACCS is mainly limited by the availability of safe and accessible geological storage, the CO_2 concentration in ambient air is 100–300 times lower than at gas- or coal-fired power plants (Sanz-Pérez et al., 2016) thus requiring more energy than flue gas CO_2 capture (Pritchard et al., 2015). This appears to be the main challenge to DACCS (Sanz-Pérez et al., 2016; Barkakaty et al., 2017).

Studies explore alternative techniques to reduce the energy penalty of DACCS (van der Giesen et al., 2017). Energy consumption could be up to 12.9 GJ tCO_2-eq^{-1}; translating into an average of 156 EJ yr^{-1} by 2100 (current annual global primary energy supply is 600 EJ); water requirements are estimated to average 0.8–24.8 km^3 $GtCO_2$-eq^{-1} yr^{-1} (Smith et al., 2016, based on Socolow et al., 2011).

However, the literature shows *low agreement* and is fragmented (Broehm et al., 2015). This fragmentation is reflected in a large range of cost estimates: from 20–1,000 USD tCO_2^{-1} (Keith et al., 2006; Pielke, 2009; House et al., 2011; Ranjan and Herzog, 2011; Simon et al., 2011; Goeppert et al., 2012; Holmes and Keith, 2012; Zeman, 2014; Sanz-Pérez et al., 2016; Sinha et al., 2017). The interquartile range (see Figure 4.2) is 40–449 USD tCO_2^{-1}; there is lower agreement and a smaller evidence base at the lower end of the cost range.

Research and efforts by small-scale commercialisation projects focus on utilisation of captured CO_2 (Wilcox

[6] FOOTNOTE: It has also been suggested that ocean alkalinity can be increased through accelerated weathering of limestone (Rau and Caldeira, 1999; Rau, 2011; Chou et al., 2015) or electrochemical processes (House et al., 2007; Rau, 2008; Rau et al., 2013b; Lu et al., 2015). However, these techniques have not been proven at large scale either (Renforth and Henderson, 2017).
[7] FOOTNOTE: This analysis relies on the assessment in Fuss et al. (2018b), which provides more detail on saturation and permanence.

et al., 2018). Given that only a few IAM scenarios incorporate DACCS (e.g., Chen and Tavoni 2013; Strefler et al. 2018a) its possible role in cost-optimised 1.5°C scenarios is not yet fully explored. Given the technology's early stage of development (McLaren, 2012; NRC, 2015a; Nemet et al., 2018) and few demonstrations (Holmes et al., 2013; Rau et al., 2013; Agee et al., 2016), deploying the technology at scale is still a considerable challenge though both optimistic (Lackner et al., 2012) and pessimistic outlooks exist (Pritchard et al., 2015).

4.3.7.6 Ocean Fertilisation

Nutrients can be added to the ocean resulting in increased biologic production, leading to carbon fixation in the sunlit ocean and subsequent sequestration in the deep ocean or sea floor sediments. The added nutrients can be either micronutrients (such as iron) or macronutrients (such as nitrogen and/or phosphorous) (Harrison 2017). There is *limited evidence* and *low agreement* on the readiness of this technology to contribute to rapid decarbonisation (Williamson et al. 2012). Only small-scale field experiments and theoretical modelling have been conducted (e.g., McLaren (2012)). The full range of CDR potential estimates is 15.2 ktCO_2 yr^{-1} (Bakker et al. 2001) for a spatially constrained field experiment to 4.4 GtCO_2 yr^{-1} (Sarmiento and Orr 1991) following a modelling approach, but Fuss et al. (2018b) consider the potential to be extremely limited given the evidence and existing barriers. Due to scavenging of iron, the iron addition only leads to inefficient use of the nitrogen in exporting carbon (Aumont and Bopp 2006; Zahariev et al. 2008; Zeebe 2005).

Cost estimates range from 2 USD tCO_2^{-1} (for iron fertilization) (Boyd and Denman 2008) to 457 USD tCO_2^{-1} (Harrison 2013). Jones (2014) proposed values greater than 20 USD tCO_2^{-1} for nitrogen fertilisation. Fertilisation is expected to impact food webs by stimulating its base organisms (Matear 2004), and extensive algal blooms may cause anoxia (Matear 2004; Russell et al. 2012; Sarmiento and Orr 1991) and deep water oxygen decline (Matear 2004), with negative impacts on biodiversity. Nutrient inputs can shift ecosystem production from an iron-limited system to a P, N-, or Si-limited system depending on the location (Bertram 2010; Matear 2004) and non-CO_2 GHGs may increase (Bertram 2010; Sarmiento and Orr 1991; Matear 2004). The greatest theoretical potential for this practice is the Southern Ocean, posing challenges for monitoring and governance (Robinson et al. 2014). The London Protocol of the International Maritime Organization has asserted authority for regulation of ocean fertilisation (Strong et al. 2009), which is widely viewed as a, de facto moratorium' on commercial ocean fertilisation activities.

There is *low agreement* in the technical literature on the permanence of CO_2 in the ocean, with estimated residence times of 1,600 years to millennia, especially if injected or buried in or below the sea floor (Williams and Druffel, 1987; Jones, 2014). Storage at the surface would mean that the carbon would be rapidly released after cessation (Aumont and Bopp 2006; Zeebe 2005).

Table 4.6: Cross-cutting issues and uncertainties across Carbon Dioxide Removal (CDR) options aspects and uncertainties

Area of uncertainty	***Cross-cutting issues and uncertainties***
Technology upscaling	• CDR options are at different stages of technological readiness (McLaren, 2012) and differ with respect to scalability. • Nemet et al. (2018) find >50% of the CDR innovation literature concerned with the earliest stages of the innovation process (R&D) identifying a dissonance between the large CO_2 removals needed in 1.5°C pathways and the long-time periods involved in scaling up novel technologies. • Lack of post-R&D literature, including incentives for early deployment, niche markets, scale-up, demand, and public acceptance.
Emerging and niche technologies	• For BECCS, there are niche opportunities with high efficiencies and fewer trade-offs (e.g., sugar and paper processing facilities (Möllersten et al., 2003), district heating (Kärki et al., 2013; Ericsson and Werner, 2016), industrial and municipal waste (Sanna et al., 2012). Turner et al. (2018) constrain potential using

	sustainability considerations and overlap with storage basins to avoid the CO_2 transportation challenge, providing a possible, though limited entry point for BECCS. • The impacts on land use, water, nutrients and albedo of BECCS could be alleviated using marine sources of biomass that could include aqua-cultured micro and macro flora (Hughes et al., 2012; Lenton, 2014) • Regarding captured CO_2 as a resource is discussed as an entry point for CDR. However, this does not necessarily lead to carbon removals, particularly if the CO_2 is sourced from fossil fuels and/or if the products do not store the CO_2 for climate-relevant horizons (von der Assen et al. 2013) (see also Section 4.3.4.5). • Methane[8] is a much more potent GHG than CO_2 (Montzka et al., 2011), associated with difficult-to-abate emissions in industry and agriculture, outgassing from lakes, wetlands, and oceans (Lockley, 2012; Stolaroff et al., 2012). Enhancing processes that naturally remove methane, either by chemical or biological decomposition (Sundqvist et al., 2012), has been proposed to remove CH_4. There is low confidence that existing technologies for methane removal are economically or energetically suitable for large-scale air capture (Boucher and Folberth, 2010). Methane removal potentials are limited due to its low atmospheric concentration and its low chemical reactivity at ambient conditions.
Ethical aspects	• Preston (2013) identifies distributive and procedural justice, permissibility, moral hazard (Shue, 2018), and hubris as ethical aspects that could apply to large-scale CDR deployment. • There is a lack of reflection on the climate futures produced by recent modelling and implying very different ethical costs/risks and benefits (Minx et al., 2018).
Governance	• Existing governance mechanisms are scarce and either targeted at particular CDR options (e.g., ocean-based) or aspects (e.g., concerning indirect land-use change (iLUC) associated with bioenergy upscaling) and often the mechanisms are at national or regional scale (e.g., EU). Regulation accounting for iLUC by formulating sustainability criteria (e.g., the EU Renewable Energy Directive) has been assessed as insufficient in avoiding leakage (e.g., Frank et al., 2013) • An international governance mechanism is only in place for R&D of Ocean Fertilisation within the Convention on Biological Diversity (IMO, 1972, 1996, CBD, 2008, 2010). • Burns and Nicholson (2017) propose a human rights-based approach to protect those potentially adversely impacted by CDR options.
Policy	• The CDR potentials that can be realised are constrained by the lack of policy portfolios incentivising large-scale CDR (Peters and Geden, 2017). • Near-term opportunities could be supported through modifying existing policy mechanisms (Lomax et al., 2015). • Scott and Geden (2018) sketch three possible routes for limited progress, (1) at EU-level, (2) at EU Member State level, and (3) at private sector level, noting the implied paradigm shift this would entail. • EU may struggle to adopt policies for CDR deployment on the scale or time-frame envisioned by IAMs (Geden et al., 2018). • Social impacts of large-scale CDR deployment (Buck, 2016) require policies taking these into account.
Carbon cycle	• On long time scales, natural sinks could reverse (C.D. Jones et al., 2016) • No robust assessments yet of the effectiveness of CDR in reverting climate change (Tokarska and Zickfeld, 2015; Wu et al., 2015; Keller et al., 2018), see also Section 2.2.2 and 2.6.2.

[8] FOOTNOTE: Current work (e.g.de Richter et al. 2017) examines other technologies considering non-CO_2 GHGs like N_2O.

4.3.8 Solar Radiation Modification (SRM)

This report refrains from using the term 'geoengineering' and separates SRM from CDR and other mitigation options (see Section 1.4.1 and Glossary).

Table 4.6 gives an overview of SRM methods and characteristics. For a more comprehensive discussion of currently proposed SRM methods, and their implications for geophysical quantities and sustainable development, see Cross-Chapter Box 10 in this Chapter. This section assesses the feasibility, from an institutional, technological, economic and social-cultural viewpoint, focusing on Stratospheric Aerosol Injection (SAI) unless otherwise indicated, as most available literature is about SAI.

Some of the literature on SRM appears in the forms of commentaries, policy briefs, viewpoints and opinions (e.g., (Horton et al., 2016; Keith et al., 2017; Parson, 2017). This assessment covers original research rather than viewpoints, even if the latter appear in peer-reviewed journals.

Table 4.7: Overview of the main characteristics of the most-studied SRM methods

	Stratospheric aerosol injection (SAI)	**Marine cloud brightening (MCB)**	**Cirrus cloud thinning (CCT)**	**Ground-based albedo modification (GBAM)**
Description of SRM method	Injection of a gas in the stratosphere, which then converts to aerosols. Injection of other particles also considered.	Spraying sea salt or other particles into marine clouds, making them more reflective.	Seeding to promote nucleation, reducing optical thickness and cloud lifetime, to allow more outgoing longwave radiation to escape into space.	Whitening roofs, changes in land use management (e.g., no-till farming), change of albedo at a larger scale (covering glaciers or deserts with reflective sheeting and changes in ocean albedo).
Radiative forcing efficiencies	1–4 TgS W^{-1} m^2 yr^{-1}	100–295 Tg dry sea salt W^{-1} m^2 yr^{-1}	Not known	Small on global scale, up to 1–3°C on regional scale
Amount needed for 1°C overshoot	2–8 TgS yr^{-1}	70 Tg dry sea salt yr^{-1}	Not known	0.04–0.1 albedo change in agricultural and urban areas
SRM specific impacts on climate variables	Changes in precipitation patterns and circulation regimes; in case of SO_2 injection disruption to stratospheric chemistry (for instance NOx depletion and changes in methane lifetime); increase in stratospheric water vapour and tropospheric-stratospheric ice formation affecting cloud microphysics.	Regional rainfall responses; reduction in hurricane intensity	Low-level cloud changes; tropospheric drying; intensification of the hydrological cycle	Impacts on precipitation in monsoon areas; could target hot extremes
SRM specific impacts on human/natural systems	In case of SO_2 injection - stratospheric ozone loss (which could also have a positive effect	Reduction in the number of mild crop failures		

	– a net reduction in global mortality due to competing health impact pathways) and significant increase of surface UV			
Maturity of science	Volcanic analogues *High agreement* amongst simulations *Robust evidence* on ethical, governance and sustainable development limitations	Observed in ships tracks Several simulations confirm mechanism Regionally limited	No clear physical mechanism *Limited evidence* and *low agreement* several simulations	Natural and land-use analogues Several simulations confirm mechanism *High agreement* to influence on regional temperature Land use costly
Key references	(Robock et al., 2008; Heckendorn et al., 2009; Tilmes et al., 2012, 2016; Pitari et al., 2014; Crook et al., 2015; C.J. Smith et al., 2017; Visioni et al., 2017a, b; Eastham et al., 2018; Plazzotta et al., 2018)	(Salter et al., 2008; Alterskjær et al., 2012; Jones and Haywood, 2012; Latham et al., 2012, 2013; Kravitz et al., 2013; Crook et al., 2015; Parkes et al., 2015; Ahlm et al., 2017)	(Storelvmo et al., 2014; Kristjánsson et al., 2015; Jackson et al., 2016; Kärcher, 2017; Lohmann and Gasparini, 2017)	(Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Seneviratne et al., 2018)

SRM could reduce some of the global risks of climate change related to temperature rise (Izrael et al., 2014; MacMartin et al., 2014), rate of sea level rise (Moore et al., 2010), sea-ice loss (Berdahl et al., 2014) and frequency of extreme storms in the North Atlantic and heatwaves in Europe (Jones et al., 2018). SRM also holds risks of changing precipitation and ozone concentrations and potentially reductions in biodiversity (Pitari et al., 2014; Visioni et al., 2017a; Trisos et al., 2018). Literature only supports SRM as a supplement to deep mitigation, for example in overshoot scenarios (Smith and Rasch, 2013; MacMartin et al., 2018).

4.3.8.1 Governance and Institutional Feasibility

There is *robust evidence* but *medium agreement* for unilateral action potentially becoming a serious SRM governance issue (Weitzman, 2015; Rabitz, 2016), as some argue that enhanced collaboration might emerge around SRM (Horton, 2011). An equitable institutional or governance arrangement around SRM would have to reflect views of different countries (Heyen et al., 2015; Robock, 2016) and be multilateral because of the risk of termination, and risks that implementation or unilateral action by one country or organisation will produce negative precipitation or extreme weather effects across borders (Lempert and Prosnitz, 2011; Dilling and Hauser, 2013; NRC, 2015b). Some have suggested that the governance of research and field experimentation can help clarify uncertainties surrounding deployment of SRM (Long and Shepherd, 2014; Parker, 2014; NRC, 2015c; Caldeira and Bala, 2017; Lawrence and Crutzen, 2017), and that SRM is compatible with democratic processes (Horton et al., 2018) or not (Szerszynski et al., 2013; Owen, 2014).

Several possible institutional arrangements have been considered for SRM governance: under the UNFCCC (in particular under the Subsidiary Body on Scientific and Technological Advice (SBSTA)) or the United Nations Convention on Biological Diversity (UNCBD) (Honegger et al., 2013; Nicholson et al., 2018), or through a consortium of states (Bodansky, 2013; Sandler, 2017). Voice in SRM diplomacy, prevention of unilateral action by others and benefits from research collaboration might be reasons for states to join an international governance framework for SRM (Lloyd and Oppenheimer, 2014).

Alongside SBSTA, the WMO, UNESCO and UN Environment could play a role in governance of SRM (Nicholson et al., 2018). Each of these organisations has relevance with respect to the regulatory framework (Bodle et al., 2012; Williamson and Bodle, 2016). The UNCBD gives guidance that 'that no climate-related geo-engineering activities that may affect biodiversity take place' (UNCBD, 2010).

4.3.8.2 Economic and Technological Feasibility

The literature on engineering cost of SRM is limited and may be unreliable in the absence of testing or deployment. There is *high agreement* that cost of SAI (not taking into account indirect and social costs, research and development costs and monitoring expenses) may be in the range of 1–10 billion USD yr^{-1} for injection of 1–5 MtS to achieve cooling of 1–2 W m^{-2} (Robock et al., 2009; McClellan et al., 2012; Ryaboshapko and Revokatova, 2015; Moriyama et al., 2016), suggesting that cost-effectiveness may be high if side-effects are low or neglected (McClellan et al., 2012). The overall economic feasibility of SRM also depends on externalities and social costs (Moreno-Cruz and Keith, 2013; Mackerron, 2014), climate sensitivity (Kosugi, 2013), option value (Arino et al., 2016), presence of climate tipping points (Eric Bickel, 2013) and damage costs as a function of the level of SRM (Bahn et al., 2015; Heutel et al., 2018). Modelling of game-theoretic, strategic interactions of states under heterogeneous climatic impacts shows *low agreement* on the outcome and viability of a cost-benefit analysis for SRM (Ricke et al., 2015; Weitzman, 2015).

For SAI, there is *high agreement* that aircrafts after some modifications could inject millions of tons of SO_2 in the lower stratosphere (~20 km; (Davidson et al., 2012; McClellan et al., 2012; Irvine et al., 2016).

4.3.8.3 Social Acceptability and Ethics

Ethical questions around SRM include those of international responsibilities for implementation, financing, compensation for negative effects, the procedural justice questions of who is involved in decisions, privatisation and patenting, welfare, informed consent by affected publics, intergenerational ethics (because SRM requires sustained action in order to avoid termination hazards), and the so-called 'moral hazard' (Burns, 2011; Whyte, 2012; Gardiner, 2013; Lin, 2013; Buck et al., 2014; Klepper and Rickels, 2014; Morrow, 2014; Wong, 2014; Reynolds, 2015; Lockley and Coffman, 2016; McLaren, 2016; Suarez and van Aalst, 2017; Reynolds et al., 2018). The literature shows *low agreement* on whether SRM research and deployment may lead policy-makers to reduce mitigation efforts and thus imply a moral hazard (Linnér and Wibeck, 2015). SRM might motivate individuals (as opposed to policymakers) to reduce their GHG emissions (Merk et al., 2016), but even a subtle difference in the articulation of information about SRM can influence subsequent judgements of favourability (Corner and Pidgeon, 2014). The argument that SRM research increases the likelihood of deployment (the 'slippery slope' argument), is also made (Parker, 2014; Quaas et al., 2017; Bellamy and Healey, 2018).

Unequal representation and deliberate exclusion are plausible in decision-making on SRM, given diverging regional interests and the anticipated low resource requirements to deploy SRM (Ricke et al., 2013). Whyte (2012) argues that the concerns, sovereignties, and experiences of Indigenous peoples may particularly be at risk.

The general public can be characterised as ignorant and worried about SRM (Carr et al., 2013; Parkhill et al., 2013; Wibeck et al., 2017). An emerging literature discusses public perception of SRM, showing a lack of knowledge and unstable opinions (Scheer and Renn, 2014). The perception of controllability affects legitimacy and public acceptability of SRM experiments (Bellamy et al., 2017). In Germany, laboratory work on SRM is generally approved of, field research much less so, and immediate deployment is largely rejected (Merk et al., 2015; Braun et al., 2017). Various factors could explain variations in the degree of rejection of SRM between Canada, China, Germany, Switzerland, the United Kingdom, and the United States (Visschers et al., 2017).

[START CROSS-CHAPTER BOX 10 HERE]

Cross-Chapter Box 10: Solar Radiation Modification in the Context of 1.5°C Mitigation Pathways

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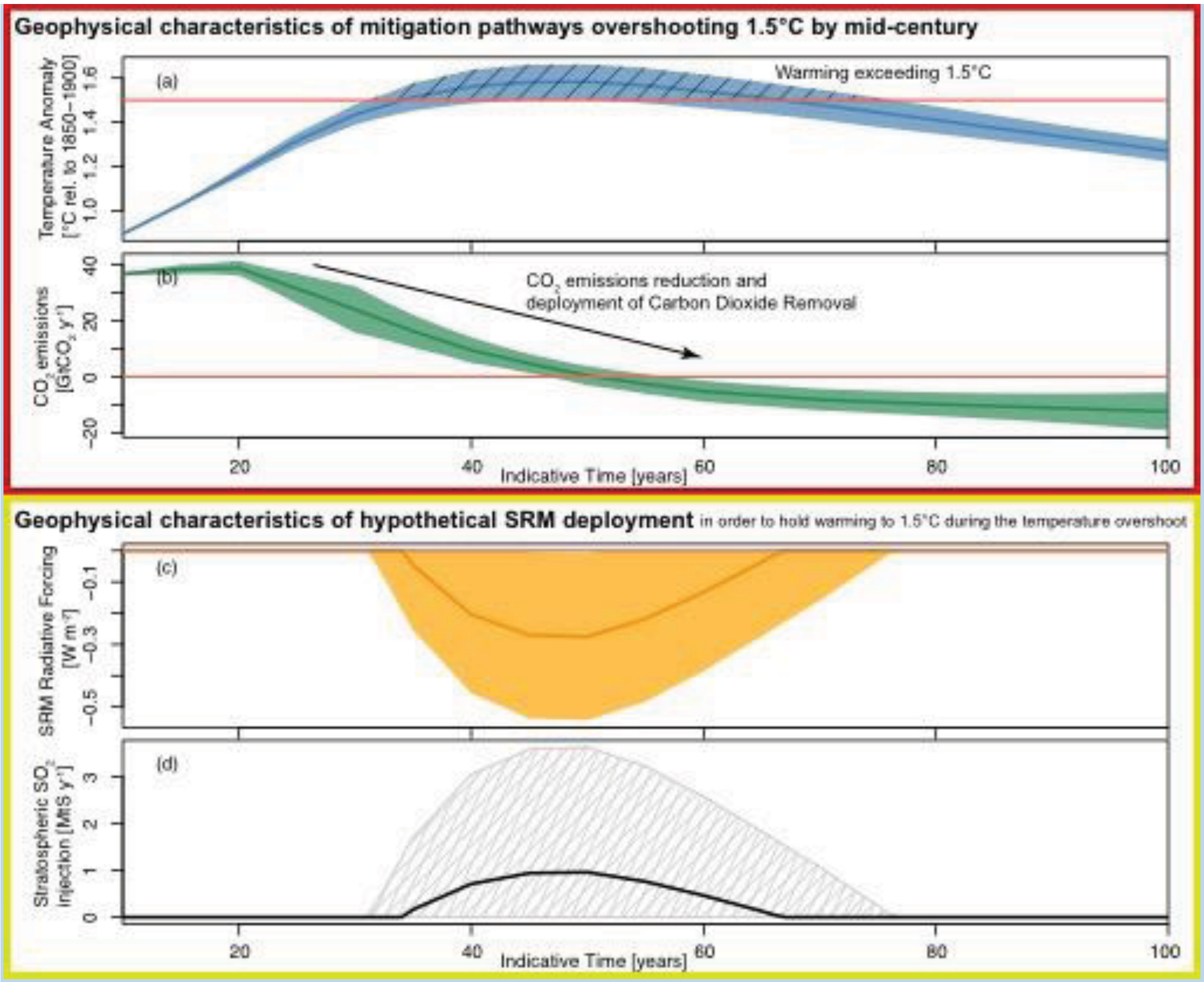
Solar Radiation Modification (SRM) refers to a range of radiation modification measures not related to Greenhouse Gas (GHG) mitigation, which seek to limit global warming (see Section 1.4.1). Most methods involve reducing the solar incoming radiation reaching the surface, but others also act on the longwave radiation budget reducing optical thickness and cloud lifetime (see Table 4.6). In the context of this report, SRM is assessed in terms of its potential to limiting warming below 1.5°C in temporary overshoot scenarios as a way to reduce elevated temperatures and associated impacts (Irvine et al., 2016; Keith and Irvine, 2016; Chen and Xin, 2017; Sugiyama et al., 2017a; Visioni et al., 2017a; MacMartin et al., 2018). The inherent variability of the climate system would make it difficult to detect the efficacy or side-effects of SRM intervention when deployed in such a temporary scenario (Jackson et al., 2015).

A. Potential SRM timing and magnitude

Published SRM approaches are summarised in Table 4.6. The timing and magnitude of potential SRM deployment depends on the temperature overshoot associated with mitigation pathways. All overshooting pathways make use of carbon dioxide removal. Therefore, if considered, SRM would only be deployed as a supplement measure to large-scale carbon dioxide removal (Section 2.3).

Cross-Chapter Box 10, Figure 1 below illustrates an example of how a hypothetical SRM deployment based on Stratospheric Aerosols Injection (SAI) could be used to limit warming below 1.5°C using an 'adaptive SRM' approach (e.g., Kravitz et al. 2011; Tilmes et al., 2016), where global mean temperature exceeds 1.5°C compared to pre-industrial level by mid-century and returns below before 2100 with a 66% likelihood (see Chapter 2). In all such limited adaptive deployment scenarios, deployment of SRM only commences under conditions in which CO_2 emissions have already fallen substantially below their peak level and are continuing to fall. In order to hold warming to 1.5°C, a hypothetical SRM deployment could span from one to several decades with the earliest possible threshold exceedance occurring before mid-century. Over this duration, SRM has to compensate for warming that exceeds 1.5°C (displayed with hatching on panel a) with a decrease in radiative forcing (panel b) which could be achieved with a rate of SAI varying between 0–5.9 $MtSO_2\ yr^{-1}$ (panel c) (Robock et al., 2008; Heckendorn et al., 2009).



Cross-Chapter Box CB10, Figure 1: Evolution of hypothetical SRM deployment (based on SAI) in the context of 1.5°C-consistent pathways. (a) Range of median temperature outcomes as simulated by MAGICC (see in Section 2.2) given the range of CO_2 emissions (b) and other climate forcers for mitigation pathways exceeding 1.5°C at mid-century and returning below by 2100 with a 66% likelihood. Geophysical characteristics are represented by the magnitude of radiative forcing (c) and the amount of stratospheric SO_2 injection (d) that are required to keep the global median temperature below 1.5°C during the temperature overshoot (given by the blue hatching on panel a). SRM surface radiative forcing has been diagnosed using a mean cooling efficiency of 0.3°C (W^{-1} m^2) of Plazzotta et al. (2018). Magnitude and timing of SO_2 injection have been derived from published estimates of Heckendorn et al. (2009) and Robock et al. (2008).

SAI is the most researched SRM method with *high agreement* that it could limit warming to below 1.5°C (Tilmes et al., 2016; Jones et al., 2018). The response of global temperature to SO_2 injection, however, is uncertain and varies depending on the model parametrisation and emission scenarios (Jones et al., 2011; Kravitz et al., 2011; Izrael et al., 2014; Crook et al., 2015; Niemeier and Timmreck, 2015; Tilmes et al., 2016; Kashimura et al., 2017). Uncertainty also arises due to the nature and the optical properties of injected aerosols.

Other approaches are less well researched but the literature suggests that Ground-Based Albedo Modification (GBAM), Marine Cloud Brightening (MCB) or Cirrus Cloud Thinning (CCT) are not assessed to be able to substantially reduce overall global temperature (Irvine et al., 2011; Seneviratne et al., 2018). However, these SRM approaches are known to create spatially heterogeneous forcing and potentially more spatially heterogeneous climate effects, which may be used to mitigate regional climate impacts. This may be of most relevance in the case of GBAM when applied to crop and urban areas (Seneviratne et al. 2018). Most of the literature on regional mitigation has focused on GBAM in relationship with land-use land cover changes scenarios. Both models and observations suggest that there is a *high agreement* that GBAM would result in cooling over the region of changed albedo, and in particular reduce hot extremes (Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Alkama and Cescatti, 2016; Seneviratne et al., 2018). In comparison, there is a *limited evidence* on the ability of MCB or CCT to mitigate regional climate impacts of 1.5°C warming because the magnitude of the climate response to MCB or CCT remains uncertain and the processes are not fully understood (Lohmann and Gasparini, 2017).

B. General consequence and impacts of solar radiation modification

It has been proposed that deploying SRM as a supplement to mitigation may reduce increases in global temperature-related extremes and rainfall intensity, and lessen the loss of coral reefs from increasing sea-surface temperatures (Keith and Irvine, 2016), but it would not address or even worsen (Tjiputra et al., 2016) negative effects from continued ocean acidification.

Another concern with SRM is the risk of a 'termination shock' or 'termination effect' when suddenly stopping SRM, which might cause rapid temperature rise and associated impacts (Jones et al., 2013; Izrael et al., 2014; McCusker et al., 2014; Robock, 2016), most noticeably biodiversity loss (Trisos et al., 2018). The severity of the termination effect has recently been debated (Parker and Irvine, 2018) and depends on the degree of SRM cooling. This report only considers limited SRM in the context of mitigation pathways to 1.5°C. Other risks of SRM deployment could be associated with the lack of testing of the proposed deployment schemes (*e.g.* (Schäfer et al., 2013)). Ethical aspects and issues related to the governance and economics are discussed in Section 4.3.8.

C. Consequences and impacts of SRM on the carbon budget

Because of its effects on surface temperature, precipitation and surface shortwave radiation, SRM would also alter the carbon budget pathways to 1.5°C or 2°C (Eliseev, 2012; Keller et al., 2014; Keith et al., 2017; Lauvset et al., 2017).

Despite the large uncertainties in the simulated climate response to SRM, current model simulations suggest that SRM would lead to altered carbon budgets compatible with 1.5°C or 2°C. The 6 CMIP5 models investigated simulated an increase of natural carbon uptake by land biosphere and, to a smaller extent, by the oceans (*high agreement*). The multi-model mean of this response suggests an increase of the RCP4.5 carbon budget of about 150 $GtCO_2$ after 50 years of SO_2 injection with a rate of 4 TgS yr^{-1}, which represents about 4 years of CO_2 emissions at the current rate (36 $GtCO_2$ yr^{-1}). However, there is uncertainty around quantitative determination of the effects that SRM or its cessation has on the carbon budget due to a lack of understanding of the radiative processes driving the global carbon cycle response to SRM (Ramachandran et al., 2000; Mercado et al., 2009; Eliseev, 2012; Xia et al., 2016), uncertainties about how the carbon cycle will respond to termination effects of SRM, and uncertainties in climate-carbon cycle feedbacks (Friedlingstein et al., 2014).

D. Sustainable development and SRM

There are few studies investigating potential implications of SRM for sustainable development. These are based on a limited number of scenarios and hypothetical considerations, mainly referring to benefits from lower temperatures (Irvine et al., 2011; Nicholson, 2013; Anshelm and Hansson, 2014; Harding and Moreno-Cruz, 2016). Other studies suggest negative impacts from SRM implementation concerning issues related to regional disparities (Heyen et al., 2015), equity (Buck, 2012), fisheries, ecosystems, agriculture, and termination effects (Robock, 2012; Morrow, 2014; Wong, 2014). If SRM is initiated by the richer nations, there might be issues with local agency, and possibly worsening conditions for those suffering most under climate change (Buck et al., 2014). In addition, ethical issues related to testing SRM have been raised (e.g., (Lenferna et al., 2017)). Overall, there is *high agreement* that SRM would affect many development issues but *limited evidence* on the degree of influence, and how it manifests itself across regions and different levels of society.

E. Overall feasibility of SRM

If mitigation efforts do not keep global mean temperature below 1.5°C, SRM can potentially reduce the climate impacts of a temporary temperature overshoot, in particular extreme temperatures, rate of sea level rise and intensity of tropical cyclones, alongside intense mitigation and adaptation efforts. While theoretical developments show that SRM is technically feasible (see Section 4.3.8.2), global field experiments have not been conducted and most of the knowledge about SRM is based on imperfect model simulations and some natural analogues. There are also considerable challenges to the implementation of SRM associated with disagreements over the governance, ethics, public perception, and distributional development impacts (Boyd, 2016; Preston, 2016; Asayama et al., 2017; Sugiyama et al., 2017b; Svoboda, 2017; McKinnon, 2018; Talberg et al., 2018) (see Section 4.3.8). Overall, the combined uncertainties surrounding the various SRM approaches, including technological maturity, physical understanding, potential impacts, and challenges of governance, constrain the ability to implement SRM in the near future.

[END CROSS-CHAPTER BOX 10 HERE]

4.4 Implementing Far-Reaching and Rapid Change

The feasibility of 1.5°C-compatible pathways is contingent upon enabling conditions for systemic change (see Cross Chapter Box 3 in Chapter 1). Section 4.3 identifies the major systems, and options within those systems, that offer the potential for change to align with 1.5°C pathways.

AR5 identifies enabling conditions as influencing the feasibility of climate responses (Kolstad et al., 2014). This section draws on 1.5°C-specific and related literature on rapid and scale-up change, to identify the enabling conditions that influence the feasibility of adaptation and mitigation options assessed in Section 4.5. Examples from diverse regions and sectors are provided to illustrate how these conditions could enable or constrain the implementation of incremental, rapid, disruptive and transformative mitigation and adaptation consistent with 1.5°C pathways.

Coherence between the enabling conditions holds potential to enhance feasibility of 1.5°C-consistent pathways and adapting to the consequences. This includes better alignment across governance scales (OECD/IEA/NEA/ITF, 2015; Geels et al., 2017), enabling multi-level governance (Cheshmehzangi, 2016; Revi, 2017; Tait and Euston-Brown, 2017) and nested institutions (Abbott, 2012). It also includes inter-disciplinary actions, combined adaptation and mitigation action (Göpfert et al., 2018) and science-policy partnerships (Vogel et al., 2007; Hering et al., 2014; Roberts, 2016; Figueres et al., 2017; Leal Filho et al., 2018). These partnerships are difficult to establish and sustain, but can generate trust (Cole, 2015; Jordan et al., 2015) and inclusivity that ultimatley can provide durability and the realisation of co-benefits for sustained rapid change (Blanchet, 2015; Ziervogel et al., 2016a).

4.4.1 Enhancing Multi-Level Governance

Addressing climate change and implementing responses to 1.5°C-consistent pathways will need to engage with various levels and types of governance (Betsill and Bulkeley, 2006; Kern and Alber, 2009; Christoforidis et al., 2013; Romero-Lankao et al., 2018). AR5 highlighted the significance of governance as a means of strengthening adaptation and mitigation and advancing sustainable development (Fleurbaey et al., 2014). Governance is defined in the broadest sense as the 'processes of interaction and decision making among actors involved in a common problem' (Kooiman 2003, Hufty 2011) (Fleurbaey et al., 2014). This definition goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions and communities.

4.4.1.1 Institutions and their Capacity to Invoke Far-Reaching and Rapid Change

Institutions, the rules and norms that guide human interactions (Section 4.4.2), enable or impede the structures, mechanisms and measures that guide mitigation and adaptation. Institutions, understood as the 'rules of the game' (North, 1990), exert direct and indirect influence over the viability of 1.5°C-consistent pathways (Munck et al., 2014; Willis, 2017). Governance would be needed to support wide-scale and effective adoption of mitigation and adaptation options. Institutions and governance structures are strengthened when the principle of the 'commons' is explored as a way of sharing management and responsibilities (Ostrom et al., 1999; Chaffin et al., 2014; Young, 2016). Institutions would need to be strengthened to interact amongst themselves, and to share responsibilities for the development and implementation of rules, regulations and policies (Ostrom et al., 1999; Wejs et al., 2014; Craig et al., 2017), with the goal of ensuring that these embrace equity, justice, poverty alleviation and sustainable development, enabling a 1.5°C world (Reckien et al., 2017; Wood et al., 2017).

Several authors have identified different modes of cross-stakeholder interaction in climate policy, including the role played by large multinational corporations, small enterprises, civil society and non-state actors. Ciplet et al. (2015) argue that civil society is to a great extent the only reliable motor for driving institutions to change at the pace required. Kern and Alber (2009) recognise different forms of collaboration relevant to successful climate policies beyond the local level. Horizontal collaboration (e.g., transnational city networks) and vertical collaboration within nation-states can play an enabling role (Ringel, 2017). Vertical and horizontal collaboration requires synergistic relationships between stakeholders (Ingold and Fischer, 2014; Hsu et al., 2017). The importance of community participation is emphasised in literature, and in particular the need to take into account equity and gender considerations (Chapter 5) (Graham et al., 2015; Bryan et al., 2017; Wangui and Smucker, 2017). Participation often faces implementation challenges and may not always result in better policy outcomes. Stakeholders, for example, may not view climate change as a priority and may not share the same preferences, potentially creating a policy deadlock (Preston et al., 2013, 2015; Ford et al., 2016).

4.4.1.2 International Governance

International treaties help strengthen policy implementation, providing a medium and long-term vision (Obergassel et al., 2016). International climate governance is organised via many mechanisms, including international organisations, treaties and conventions, for example, UNFCCC, the Paris Agreement and the Montreal Protocol. Other multilateral and bilateral agreements, such as trade agreements, also have a bearing on climate change.

There are significant differences between global mitigation and adaptation governance frames. Mitigation tends to be global by its nature and it is based on the principle of the climate system as a global commons (Ostrom et al., 1999). Adaptation has traditionally been viewed as a local process, involving local authorities, communities, and stakeholders (Khan, 2013; Preston et al., 2015), although is now recognised to be a multi-scaled, multi-actor process that transcends from local and sub-national, to national and international scales (Mimura et al., 2014; UNEP, 2017a). National governments provide a central pivot for coordination, planning, determining policy (Section 4.4.5) priorities and distributing resources. National governments are accountable to the international community through international agreements. Yet, many of the impacts of climate change are transboundary, so that bilateral and multilateral cooperation are needed (Nalau et al., 2015; Donner et al., 2016; Magnan and Ribera, 2016; Tilleard and Ford, 2016; Lesnikowski et al., 2017). The Kigali Amendment to the Montreal Protocol demonstrates that a global environmental agreement facilitating common but differentiated responsibilities is possible (Sharadin, 2018). This was operationalised by developed countries acting first, with developing countries following and benefiting from leap-frogging the trial-and-error stages of innovative technology development.

Work on international climate governance has focused on the nature of 'climate regimes' and coordinating the action of nation-states (Aykut, 2016) organised around a diverse set of intruments: i) binding limits allocated by principles of historical responsibility and equity, ii) carbon prices, emissions quotas, iii) pledges and review of policies and measures or iv) a combination of these options (Stavins, 1988; Grubb, 1990; Pizer, 2002; Newell and Pizer, 2003).

Literature on the Kyoto Protocol provides two important insights for 1.5°C transition: the challenge of agreeing on rules to allocate emissions quotas (Shukla, 2005; Caney, 2012; Winkler et al., 2013; Gupta, 2014; Méjean et al., 2015) and a climate-centric vision (Shukla, 2005; Winkler et al., 2011), separated from development issues which drove resistance from many developing nations (Roberts and Parks, 2006). For the former, a burden sharing approach led to an adversarial process among nations to decide who shall be allocated 'how much' of the remainder of the emissions budget (Caney, 2014; Ohndorf et al., 2015; Roser et al., 2015; Giménez-Gómez et al., 2016). Industry group lobbying, further contributed to reducing space for maneuvre of some major emitting nations (Newell and Paterson, 1998; Levy and Egan, 2003; Dunlap and McCright, 2011; Michaelowa, 2013; Geels, 2014).

Given the political unwillingness to continue with the Kyoto Protocol approach a new approach was introduced in the Copenhagen Accord, the Cancun Agreements, and finally in the Paris Agreement. The transition to 1.5°C requires carbon neutrality and thus going beyond the traditional framing of climate as a 'tragedy of the commons' to be addressed via cost-optimal allocation rules, which demonstrated a low probability of enabling a transition to 1.5°C consistent pathways (Patt, 2017). The Paris Agreement, built on a 'pledge and review'-system is thought be more effective in securing trust (Dagnet et al., 2016), enables effective monitoring and timely reporting on national actions (including adaptation), allowing for international scrutiny and persistent efforts of civil society and non-state actors to encourage action in both national and international contexts (Allan and Hadden, 2017; Bäckstrand and Kuyper, 2017; Höhne et al., 2017; Lesnikowski et al., 2017; Maor et al., 2017; UNEP, 2017a), with some limitations (Nieto et al., 2018).

The paradigm shift enabled at Cancun succeeded by focusing on the objective of 'equitable access to sustainable development' (Hourcade et al., 2015). The use of 'pledge and review' now underpins the Paris Agreement. This consolidates multiple attempts to define a governance approach that relies on National Determined Contributions (NDCs) and on means for a 'facilitative model' (Bodansky and Diringer, 2014) to reinforce them. This enables a regular, iterative, review of NDCs allowing countries to set their own ambitions after a global stocktake and more flexible, experimental forms of climate governance, which may provide room for higher ambition, and be consistent with the needs of governing for a rapid transition to close the emission gap (Clémençon, 2016; Falkner, 2016) (Cross-Chapter Box11 in this Chapter). Beyond a general consensus on the necessity of Measurement, Reporting and Verification (MRV) mechanisms as a key element of a climate regime (Ford et al., 2015b; van Asselt et al., 2015), some authors emphasise different governance approaches to implement the Paris Agreement. Through market mechanisms under Article 6 of the Paris Agreement and the new proposed sustainable development mechanism, it allows the space to harness the lowest cost mitigation options worldwide. This may incentivise policymakers to enhance mitigation ambition by speeding up climate action as part of 'climate regime complex' (Keohane and Victor, 2011) of loosely interrelated global governance institutions. In the Paris Agreement, the Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC) principle could be expanded and revisited under a 'sharing the pie' paradigm (Ji and Sha, 2015) as a tool to open innovation processes towards alternative development pathways (Chapter 5).

COP16 in Cancun was also the first time in the UNFCCC that adaptation was recognised to have similar priority as mitigation. The Paris Agreement recognises the importance of adaptation action and cooperation to enhance such action. (Chung Tiam Fook, 2017; Lesnikowski et al., 2017) suggest that the Paris Agreement is explicit about multilevel adaptation governance, outlines stronger transparency mechanisms, links adaptation to development and climate justice, and is hence, suggestive of greater inclusiveness of non-state voices and the broader contexts of social change.

1.5°C-consistent pathways require further exploration of conditions of trust and reciprocity amongst nation states (Schelling, 1991; Ostrom and Walker, 2005). Some authors (Colman et al., 2011; Courtois et al., 2015) suggest a departure from the vision of actors acting individually in the pursuit of self-interest to that of iterated games with actors interacting over time showing that reciprocity, with occasional forgiveness and initial good faith, can lead to win-win outcomes and to cooperation as a stable strategy (Axelrod and Hamilton, 1981).

Regional cooperation plays an important role in the context of global governance. Literature on climate regimes has only started exploring innovative governance arrangements including: coalitions of transnational actors including state, market and non-state actors (Bulkeley et al., 2012; Hovi et al., 2016; Hagen et al., 2017; Hermwille et al., 2017; Roelfsema et al., 2018) and groupings of countries, as a complement to the

UNFCCC (Abbott and Snidal, 2009; Biermann, 2010; Zelli, 2011; Nordhaus, 2015). Climate action requires multi-level governance from the local and community level to national, regional and international levels. Box 4.1 shows the role of sub-national authorities, e.g. regions and provinces in facilitating urban climate action, while Box 4.2 shows that climate governance can be organised across hydrological and not only political units as well.

4.4.1.3 Sub-National Governance

Local governments can play a key role (Melica et al., 2018; Romero-Lankao et al., 2018) in influencing mitigation and adaptation strategies. It is important to understand how rural and urban areas, small islands, informal settlements and communities might intervene to reduce climate impacts (Bulkeley et al., 2011), either by implementing climate objectives defined at higher government levels, taking initiative autonomously or collectively (Aall et al., 2007; Reckien et al., 2014; Araos et al., 2016a; Heidrich et al., 2016). Local governance faces the challenge of reconciling local concerns with global objectives. Local governments could coordinate and develop effective local responses, and could pursue procedural justice in ensuring community engagement and more effective policies around energy and vulnerability reduction (Moss et al., 2013; Fudge et al., 2016). They can enable more participative decision-making (Barrett, 2015; Hesse, 2016). Fudge et al. (2016) argue that local authorities are well-positioned to involve the wider community in: designing and implementing climate policies, engaging with sustainable energy generation, e.g., by supporting energy communities (Slee, 2015), and the delivery of demand-side measures and adaptation implementation.

By 2050, it is estimated three billion people will be living in slums and informal settlements: neighbourhoods without formal governance, on un-zoned land developments and in places that are exposed to climate-related hazards (Bai et al., 2018). Emerging research is examining how citizens can contribute informally to governance with rapid urbanisation and weaker government regulation (Sarmiento and Tilly, 2018). It remains to be seen how the possibilities and consequences of alternative urban governance models for large, complex problems and addressing inequality and urban adaptation will be managed (Amin and Cirolia, 2018; Bai et al., 2018; Sarmiento and Tilly, 2018).

Expanding networks of cities sharing experiences on coping with climate change and drawing economic and development benefits from climate change responses represent a recent institutional innovation. This could be complemented by efforts of national governments through national urban policies to enhance local climate action (Broekhoff et al., 2018). Over the years, non-state actors have set up several transnational climate governance initiatives to accelerate the climate response, for example ICLEI (1990), C–40 (2005), the Global Island Partnership (2006) and the Covenant of Mayors (2008) (Gordon and Johnson, 2017; Hsu et al., 2017; Ringel, 2017; Kona et al., 2018; Melica et al., 2018) and to exert influence on national governments and the UNFCCC (Bulkeley, 2005). However, (Michaelowa and Michaelowa, 2017) find low effectiveness of over 100 of such mitigation initiatives.

4.4.1.4 Interactions and Processes for Multi-Level Governance

Literature has proposed multi-level governance in climate change as an enabler for systemic transformation and effective governance, as the concept is thought to allow for combining decisions across levels, sectors and institutional types at the same level (Romero-Lankao et al., 2018) with multi-level reinforcement and the mobilisation of economic interests at different levels of governance (Janicke and Quitzow, 2017). These governance mechanisms are based on accountability and transparency rules and participation and coordination across and within these levels.

A study of 29 European countries showed that the rapid adoption and diffusion of adaptation policymaking is largely driven by internal factors, at the national and sub-national levels (Massey et al., 2014). An assessment of national level adaptation in 117 countries (Berrang-Ford et al., 2014), find good governance to be the one of the strongest predictors of national adaptation policy. An analysis of climate response by 200 large and medium-sized cities across eleven European countries find that factors such as membership of climate networks, population size, Gross Domestic Product (GDP) per capita and adaptive capacity act as drivers of mitigation and adaptation plans (Reckien et al., 2015).

Adaptation policy has seen growth in some areas (Massey et al., 2014; Lesnikowski et al., 2016), although efforts to track adaptation progress are constrained by an absence of data sources on adaptation (Berrang-Ford et al. 2011; Ford and Berrang-Ford 2016; Magnan and Ribera 2016; Magnan 2016). Many developing countries have made progress in formulating national policies, plans and strategies on responding to climate change. The NDCs have been identified as one such institutional mechanism (Magnan et al., 2015; Kato and Ellis, 2016; Peters et al., 2017) (Cross-Chapter Box11 in this Chapter).

To overcome barriers to policy implementation, local conflicts of interest or vested interests, strong leadership and agency is needed by political leaders. As shown by the Covenant of Mayors initiative (Box 4.1), political leaders with a vision for the future of the local community can succeed in reducing GHG emissions, when they are supported by civil society (Rivas et al., 2015; Croci et al., 2017; Kona et al., 2018). Any political vision would need to be translated into an action plan, of which elements could be describing policies and measures needed to achieve transition, the human and financial resources needed, milestones, and appropriate measurement and verification processes (Azevedo and Leal, 2017). Discussing the plan with stakeholders and civil society, including citizens and right of participation for minorities, and having them provide input and endorse it, is found to increase the likelihood of success (Rivas et al., 2015; Wamsler, 2017). However, as described by Nightingale (2017) and Green (2016), struggles over natural resources and adaptation governance both at the national and community levels would need to be addressed too, 'in politically unstable contexts, where power and politics shape adaptation outcomes'.

[START BOX 4.1 HERE]

Box 4.1: Multi-Level Governance in the EU Covenant of Mayors: Example of the Provincia di Foggia

Since 2005, cities have emerged as a locus of institutional and governance climate innovation (Melica et al., 2018) and are driving responses to climate change (Roberts, 2016). Many cities have adopted more ambitious Greenhouse Gas (GHG) emission reduction targets than countries (Kona et al., 2018), with an overall commitment of GHG emission reduction targets by 2020 of 27%, almost 7 percentage points higher than the minimum target for 2020 (Kona et al., 2018). The Covenant of Mayors (CoM) is an initiative in which municipalities voluntarily commit to CO_2 emission reduction. The participation of small municipalities has been facilitated by the development and testing of a new multi-level governance model involving Covenant Territorial Coordinators (CTCs), i.e., provinces and regions, which commit to providing strategic guidance, financial and technical support to municipalities in their territories. Results from the 315 monitoring inventories submitted shows an achievement of 23% reduction in emissions (compared to an average year 2005) of more than half of the cities under a CTC schema (Kona et al., 2018).

The Province of Foggia, acting as a CTC, gave support to 36 municipalities to participate in the CoM and to prepare Sustainable Energy Action Plans (SEAPs). The Province developed a common approach to prepare SEAPs, provided data to compile municipal emission inventories (Bertoldi et al., 2018) and guided the signatory to identify an appropriate combination of measures to curb GHG emissions programme. The local Chamber of Commerce had a key role also in the implementation of these projects by the municipalities (Lombardi et al., 2016). The joint action by the province and the municipalities in collaboration with the local business community could be seen as an example of multi-level governance (Lombardi et al., 2016).

Researchers have investigated local forms of collaboration within local government, with the active involvement of citizens and stakeholders, and acknowledge that public acceptance is key to the successful implementation of policies (Larsen and Gunnarsson-Östling, 2009; Musall and Kuik, 2011; Pollak et al., 2011; Christoforidis et al., 2013; Pasimeni et al., 2014; Lee and Painter, 2015). Achieving ambitious targets would need leadership, enhanced multi-level governance, vision and widespread participation in transformative change (Castán Broto and Bulkeley, 2013; Rosenzweig et al., 2015; Castán Broto, 2017;

Fazey et al., 2017; Wamsler, 2017; Romero-Lankao et al., 2018). The Section 5.6.4 case studies of climate-resilient development pathways, at state and community scales, show that participation, social learning and iterative decision-making are governance features of strategies that deliver mitigation, adaptation, and sustainable development in a fair and equitable manner. Other insights include that incremental voluntary changes are amplified through community networking, poly-centric governance (Dorsch and Flachsland, 2017) and partnerships and long-term change to governance systems at multiple levels (Stevenson and Dryzek, 2014; Lövbrand et al., 2017; Pichler et al., 2017; Termeer et al., 2017).

[END BOX 4.1 HERE]

Multilevel governance includes adaptation across local, regional, and national scales (Adger et al., 2005). The whole-of-government approach to understanding and influencing climate change policy design and implementation puts analytical emphasis on how different levels of government and different types of actors (e.g., public and private) can constrain or support local adaptive capacity (Corfee-Morlot et al., 2011), including the role of the civil society. National governments, for example, have been associated with enhancing adaptive capacity through building awareness of climate impacts, encouraging economic growth, providing incentives, establishing legislative frameworks conducive to adaptation, and communicating climate change information (Berrang-Ford et al., 2014; Massey et al., 2014; Austin et al., 2015; Henstra, 2016; Massey and Huitema, 2016). Local governments, on the other hand, are responsible for delivering basic services and utilities to the urban population, and protecting their integrity from the impacts of extreme weather (Austin et al., 2015; Cloutier et al., 2015; Nalau et al., 2015; Araos et al., 2016b). National policies and transnational governance could be seen as complementary, rather than competitors, and strong national policies favour sub- and non-state actors to engage transnationally (Andonova et al., 2017). Local initiatives are complementary with higher level policies and can be integrated in the multi-level governance system (Fuhr et al., 2018).

A multilevel approach considers that adaptation planning is affected by scale mismatches between the local manifestation of climate impacts and the diverse scales at which the problem is driven (Shi et al., 2016). Multilevel approaches may be relevant in low-income countries where limited financial resources and human capabilities within local governments often lead to greater dependency on national governments and other (donor) organisations, to strengthen adaptation responses (Donner et al., 2016; Adenle et al., 2017). National governments or international organisations may motivate urban adaptation externally through broad policy directives or projects by international donors. Municipal governments on the other hand work within the city to spur progress on adaptation. Individual political leadership in municipal government, for example, has been cited as a factor driving adaptation policy of early adapters in Quito, Ecuador, and Durban, South Africa (Anguelovski et al., 2014), and for adaptation more generally (Smith et al., 2009). Adaptation pathways can help identify maladaptive actions (Juhola et al., 2016; Magnan et al., 2016; Gajjar et al., 2018) and encourage social learning approaches across multiple levels of stakeholders in sectors such as marine biodiversity and water supply (Bosomworth et al., 2015; Butler et al., 2015; van der Brugge and Roosjen, 2015).

Box 4.2 exemplifies how multilevel governance has been used for watershed management in different basins, given the impacts on water sources (Section 3.4.2).

[START BOX 4.2 HERE]

Box 4.2: Watershed Management in a 1.5˚C World

Water management is necessary if the global community would adapt to 1.5°C-consistent pathways. Cohesive planning that includes numerous stakeholders will be required to improve access, utilisation and efficiency of water use and ensure hydrologic viability.

Response to drought and El Niño Southern Oscillation (ENSO) in Southern Guatemala
Hydro-meteorological events, including the ENSO, have impacted Central America (Steinhoff et al., 2014; Chang et al., 2015; Maggioni et al., 2016) and are projected to increase in frequency during a 1.5°C

transition (Wang et al., 2017). The 2014–2016 ENSO damaged agriculture, seriously impacting rural communities.

In 2016, the Climate Change Institute, in conjunction with local governments, the private sector, communities and human rights organisations, established dialogue tables for different watersheds to discuss water usage amongst stakeholders and plans to mitigate the effects of drought, ameliorate social tension, and map water use of watersheds at risk. The goal was to encourage better water resource management and to enhance ecological flow through improved communication, transparency, and coordination amongst users. These goals were achieved in 2017 when each previously affected river reached the Pacific Ocean with at least its minimum ecological flow (Guerra, 2017).

Drought management through the Limpopo Watercourse Commission

The governments sharing the Limpopo river basin (Botswana, Mozambique, South Africa and Zimbabwe) formed the Limpopo Watercourse Commission in 2003 (Nyagwambo et al., 2008; Mitchell, 2013). It has an advisory body comprised of working groups that assess water use and sustainability, decides national level distribution of water access, and supports disaster and emergency planning. The Limpopo basin delta is highly vulnerable (Tessler et al., 2015), and is associated with a lack of infrastructure and investment capacity, requiring increased economic development together with plans for vulnerability reduction (Tessler et al., 2015) and water rights (Swatuk, 2015). The high vulnerability is influenced by gender inequality, limited stakeholder participation and institutions to address unequal water access (Mehta et al., 2014). The implementation of Integrated Water Resources Management (IWRM) would need to consider pre-existing social, economic, historical and cultural contexts (Merrey, 2009; Mehta et al., 2014). The Commission therefore could play a role in improving participation and in providing an adaptable and equitable strategy for cross-border water sharing (Ekblom et al., 2017).

Flood management in the Danube

The Danube River Protection Convention is the official instrument for cooperation on transboundary water governance between the countries that share the Danube Basin. The International Commission for the Protection of the Danube River (ICPDR) provides a strong science-policy link through expert working groups dealing with issues including governance, monitoring and assessment and flood protection (Schmeier, 2014). The Trans-National Monitoring Network (TNMN) was developed to undertake comprehensive monitoring of water quality (Schmeier, 2014). Monitoring of water quality constitutes almost 50% of ICPDR's scientific publications, which also works on governance, basin planning, monitoring, and IWRM, indicating the importance. The ICPDR is an example of IWRM ‘coordinating groundwater, surface water abstractions, flood management, energy production, navigation, and water quality’ (Hering et al., 2014).

[END BOX 4.2 HERE]

[START CROSS-CHAPTER BOX 11 HERE]

Cross-Chapter Box 11: Consistency Between Nationally Determined Contributions and 1.5°C Scenarios

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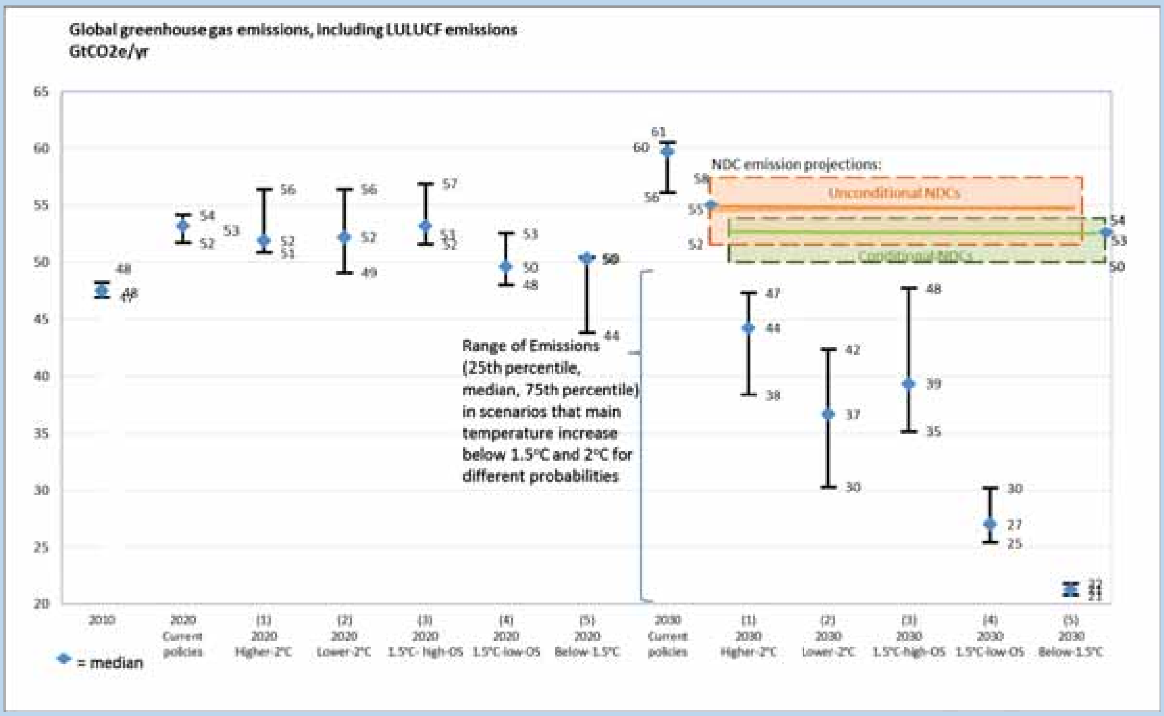
Mitigation

1. Introduction

There is *high agreement* that Nationally Determined Contributions (NDCs) are important for the global response to climate change and represent an innovative bottom-up instrument in climate change governance (Section 4.4.1), with contributions from all signatory countries (den Elzen et al., 2016; Rogelj et al., 2016; Vandyck et al., 2016; Luderer et al., 2018; Vrontisi et al., 2018). The global emission projection resulting from full implementation of the NDCs represent an improvement compared to business as usual (Rogelj et al., 2016) and current policies scenarios to 2030 (den Elzen et al., 2016; Vrontisi et al., 2018). Most G20 economies would require new policies and actions to achieve their NDC targets (den Elzen et al., 2016; Vandyck et al., 2016; Kuramochi et al., 2017; UNEP, 2017b).

2. The effect of NDCs on global Greenhouse Gas (GHG) emissions

Several studies estimate global emission levels that would be achieved under the NDCs (e.g., den Elzen et al., 2016; Luderer et al., 2016; Rogelj et al., 2016, 2017; Vandyck et al., 2016; Rose et al., 2017; Vrontisi et al., 2018). Rogelj et al. (2016) and (UNEP, 2017b) concluded that the full implementation of the unconditional and conditional NDCs are expected to result in global GHG emissions of about 55 (52–58) and 53 (50–54) $GtCO_2$-eq yr^{-1}, respectively (Cross-Chapter Box 11, Figure 1 below).



Cross-Chapter Box 11, Figure 1: GHG emissions are all expressed in units of CO_2-equivalence computed with 100-year Global Warming Potentials (GWPs) reported in IPCC SAR, while the emissions of the 1.5°C and 2°C scenarios in Table 2.4 are reported using the 100-year GWPs reported in IPCC AR4, and are hence about 3% higher. Using IPCC AR4 instead of SAR GWP values is estimated to result in a 2-3% increase in estimated 1.5°C and 2°C emissions levels in 2030. Source: based on Rogelj et al. (2016) and UNEP (2017b).

3. The effect of NDCs on temperature increase and carbon budget

Estimates of global average temperature increase are 2.9–3.4°C above preindustrial levels with a greater than 66% probability by 2100 (Rogelj et al., 2016; UNEP, 2017b), under a full implementation of unconditional NDCs and a continuation of climate action similar to that of the NDCs. Full implementation of the conditional NDCs would lower the estimates by about 0.2°C by 2100. As an indication of the carbon budget implications of NDC scenarios, Rogelj et al. (2016) estimated cumulative emissions in the range of 690 to 850 $GtCO_2$ for the period 2011–2030 if the NDCs are successfully implemented. The carbon budget for post-2010 till 2100 emissions compatible with staying below 1.5°C with a 50–66% probability was estimated at 550–600 $GtCO_2$ (Clarke et al., 2014; Rogelj et al., 2016), which will be well exceeded by 2030 at full implementation of the NDCs. This estimate has been updated (Section 2.2 and Section 2.3.1).

4. The 2030 emissions gap with 1.5ºC and urgency of action
As the 1.5°C pathways require reaching carbon neutrality by mid-century, the NDCs alone are not sufficient, as they have a time horizon until 2030. (Rogelj et al., 2016; Hof et al., 2017) have used results or compared NDC pathways with emissions pathways produced by Integrated Assessment Models (IAMs) assessing the contribution of NDCs to achieve the 1.5°C targets. There is *high agreement* that current NDC emission levels are not in line with pathways that limit warming to 1.5°C by the end of the century (Rogelj et al., 2016, 2017; Hof et al., 2017; UNEP, 2017b; Vrontisi et al., 2018). The median 1.5°C emissions gap (>66% chance) for the full implementation of both the conditional and unconditional NDCs for 2030 is 26 (19–29) to 28 (22–33) $GtCO_2$-eq (Cross-Chapter Box 11, Figure 1 above).

Studies indicate important trade-offs of delaying global emissions reductions (Sections 2.3.5 and 2.5.1). AR5 identified flexibility in 2030 emission levels when pursuing a 2°C objective (Clarke et al., 2014) indicating that strongest trade-offs for 2°C pathways could be avoided if emissions are limited to below 50 $GtCO_2$-eq yr^{-1} in 2030 (here computed with the GWP–100 metric of the IPCC SAR). New scenario studies show that full implementation of the NDCs by 2030 would imply much deeper and faster emission reductions beyond 2030 in order to meet 2ºC, and also higher costs and efforts of negative emissions (Fujimori et al., 2016; Sanderson et al., 2016; Rose et al., 2017; van Soest et al., 2017; Luderer et al., 2018). However, no flexibility has been found for 1.5°C pathways (Luderer et al., 2016; Rogelj et al., 2017) indicating that post–2030 emissions reductions required to remain within a 1.5°C compatible carbon budget during the 21st century (Section 2.2) are not within the feasible operating space of IAMs. This indicates that failing to reach a 1.5°C pathway are significantly increased (Riahi et al., 2015), if near-term ambition is not strengthened beyond the level implied by current NDCs.

Accelerated and stronger short-term action and enhanced longer-term national ambition going beyond the NDCs would be needed for 1.5°C-consistent pathways. Implementing deeper emissions reduction than current NDCs would imply action towards levels identified in Section 2.3.3, either as part of or over-delivering on NDCs.

5. *The impact of uncertainties on NDC emission levels*
The measures proposed in NDCs are not legally binding (Nemet et al., 2017), further impacting estimates of anticipated 2030 emission levels. The aggregation of targets results in high uncertainty (Rogelj et al., 2017), which could be reduced with clearer guidelines for compiling future NDCs focused more on energy accounting (Rogelj et al., 2017) and increased transparency and comparability (Pauw et al., 2018).

Many factors would influence NDCs global aggregated effects, including: (1) variations in socioeconomic conditions, (Gross Domestic Product, GDP, and population growth), (2) uncertainties in historical emission inventories, (3) conditionality of certain NDCs, (4) definition of NDC targets as ranges instead of single values, (5) the way in which renewable energy targets are expressed, and (6) the way in which traditional biomass use is accounted for. Additionally, there are land-use mitigation uncertainties (Forsell et al., 2016; Grassi et al., 2017). Land-use options play a key role in many country NDCs, however, many analyses on NDCs do not use country estimates on land-use emissions, but use model estimates, mainly because of the large difference in estimating the "anthropogenic" forest sink between countries and models (Grassi et al., 2017).

7. Comparing countries' NDC ambition (equity, cost optimal allocation and other indicators)
Various assessment frameworks have been proposed to analyse, benchmark and compare NDCs, and indicate possible strengthening, based on equity and other indicators (Aldy et al., 2016; den Elzen et al., 2016; Höhne et al., 2017; Jiang et al., 2017; Holz et al., 2018).There is large variation in conformity/fulfillment with equity principles across NDCs and countries. Studies use assessment frameworks based on six effort sharing categories in the AR5 (Clarke et al., 2014) with the principles of 'responsibility', 'capability' and 'equity' (Höhne et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017). There is an important methodological gap in the assessment of the NDCs' fairness and equity implications, partly due to lack of information on countries' own assessment (Winkler et al., 2017). Implementation of Article 2.2 of the Paris Agreement could reflect equity and the principle of common but differentiated

responsibilities and respective capabilities, due to different national circumstances and different interpretations of equity principles (Lahn, 2017; Lahn and Sundqvist, 2017).

Adaptation

The Paris Agreement recognises adaptation by establishing a global goal for adaptation (Kato and Ellis, 2016; Rajamani, 2016; Kinley, 2017; Lesnikowski et al., 2017; UNEP, 2017a). This is assessed qualitatively, as achieve a temperature goal, would determine the level of ambition of addressing adaptation to consequent risks and impacts (Rajamani, 2016). Countries can include domestic adaptation goals in their NDCs, which together with National Adaptation Plans (NAPs) give countries flexibility to design and adjust their adaptation trajectories as their needs evolve and as progress is evaluated over time. A challenge for assessing progress on adaptation globally is the aggregation of many national adaptation actions and approaches. Knowledge gaps still remain about how to design measurement frameworks that generate and integrate national adaptation data without placing undue burdens on countries (UNEP, 2017a).

The Paris Agreement stipulates that adaptation communications shall be submitted as a component of or in conjunction with other communications, such as an NDC, a NAP, or a National Communication. Of the 197 Parties to the UNFCCC, 140 NDCs have an adaptation component, almost exclusively from developing countries. NDC adaptation components could be an opportunity for enhancing adaptation planning and implementation by highlighting priorities and goals (Kato and Ellis, 2016). At the national level they provide momentum for the development of NAPs and raise the profile of adaptation (Pauw et al., 2016b, 2018). The Paris Agreement's transparency framework includes adaptation, through which 'adaptation communication' and accelerated adaptation actions are submitted and reviewed every five years (Hermwille, 2016; Kato and Ellis, 2016). This framework, unlike others used in the past, is applicable to all countries taking into account differing capacities amongst Parties (Rajamani, 2016).

Adaptation measures presented in qualitative terms include sectors, risks and vulnerabilities that are seen as priorities by the Parties. Sectoral coverage of adaptation actions identified in NDCs is uneven, with adaptation primarily reported to focus on the water sector (71% of NDCs with adaptation component), agriculture (63%), and health (54%), and biodiversity/ecosystems (50%) (Pauw et al., 2016b, 2018).

[END CROSS-CHAPTER BOX 11 HERE]

4.4.2 Enhancing Institutional Capacities

The implementation of sound responses and strategies to enable a transition to 1.5°C world would require strengthening governance and scaling up institutional capacities, particularly in developing countries (Adenle et al., 2017; Rosenbloom, 2017). Building on the characterisation of governance in Section 4.4.1, this section examines the necessary institutional capacity to implement actions to limit warming to 1.5°C and adapt to the consequences. This takes into account a plurality of regional and local responses, as institutional capacity is highly context-dependent (North, 1990; Lustick et al., 2011).

Institutions would need to interact with one another and align across scales to ensure that rules and regulations are followed (Chaffin and Gunderson, 2016; Young, 2016). The institutional architecture required for a 1.5°C world would include the growing proportion of the world's population that live in peri-urban and informal settlements and engage in informal economic activity (Simone and Pieterse, 2017). This population, amongst the most exposed to perturbed climates in the world (Hallegatte et al., 2017), is also beyond the direct reach of some policy instruments (Jaglin, 2014; Thieme, 2017). Strategies that accommodate the informal rules of the game adopted by these populations have large chances of success (McGranahan et al., 2016; Kaika, 2017).

The goal for strengthening implementation is to ensure that these rules and regulations embrace equity, equality and poverty alleviation along 1.5°C-consistent pathways (mitigation) and enables the building of adaptive capacity that together, will enable sustainable development and poverty reduction.

Rising to the challenge of a transition to a 1.5°C world would require enhancing institutional climate change capacities along multiple dimensions presented below.

4.4.2.1 Capacity for Policy Design and Implementation

The enhancement of institutional capacity for integrated policy design and implementation has long been among the top items on the UN agenda of addressing global environmental problems and sustainable development (UNEP, 2005) (see Section 5.5).

Political stability, an effective regulatory and enforcement framework (e.g., institutions to impose sanctions, collect taxes and to verify building codes), access to a knowledge base and the availability of resources, would be needed at various governance levels, to address a wide range of stakeholders, and their concerns. The strengthening of the global response would need to support these with different interventions, in the context of sustainable development(Pasquini et al., 2015) (Section 5.5.1).

Given the scale of change needed to achieve 1.5°C, strengthening the response capacity of relevant institutions are best addressed in ways that take advantage of existing decision-making processes in local and regional governments and within cities and communities (Romero-Lankao et al., 2013), and draw upon diverse knowledge sources including Indigenous and local knowledge (Nakashima et al., 2012; Smith and Sharp, 2012; Mistry and Berardi, 2016; Tschakert et al., 2017). Examples of successful local institutional processes and the integration of local knowledge in climate-related decisions making are provided in Box 4.3 and Box 4.4.

Implementing 1.5°C-relevant strategies would require well-functioning legal frameworks to be in place, in conjunction with clearly defined mandates, rights and responsibilities to enable the institutional capacity to deliver (Romero-Lankao et al., 2013). As an example, current rates of urbanisation occurring in cities with a lack of institutional capacity for effective land-use planning, zoning and infrastructure development, result in unplanned, informal urban settlements which are vulnerable to climate impacts. It is common for 30–50% of urban populations in low-income nations to live in informal settlements with no regulatory infrastructure (Revi et al., 2014b). For example, in Huambo (Angola), a classified 'urban' area extends 20km west of the city and is predominantly made up of 'unplanned' urban settlements (Smith and Jenkins, 2015).

Internationally, the Paris Agreement process has aimed at enhancing the capacity of decision-making institutions in developing countries to support effective implementation. These efforts are particularly reflected in Article 11 of the Paris Agreement on capacity building (the creation of the Paris Committee on Capacity Building), Article 13 (the creation of the Capacity Building Initiative on Transparency), as well as Article 15 on compliance (UNFCCC, 2015).

[START BOX 4.3 HERE]

Box 4.3: Indigenous Knowledge and Community Adaptation

Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO, 2017). This knowledge can underpin the development of adaptation and mitigation strategies (Ford et al., 2014b; Green and Minchin, 2014; Pearce et al., 2015; Savo et al., 2016).

Climate change is an important concern for the Maya, who depend on climate knowledge for their livelihood. In Guatemala, the collaboration between the Mayan K'iché population of the Nahualate river basin and the Climate Change Institute has resulted in a catalogue of Indigenous knowledge, used to identify indicators for watershed meteorological forecasts (Yax L. and Álvarez, 2016). These indicators are relevant but would need continuous assessment if their continued reliability is to be confirmed (Nyong et al., 2007;

Alexander et al., 2011; Mistry and Berardi, 2016). For more than ten years, Guatemala has maintained an 'Indigenous Table for Climate Change', to enable the consideration of indigenous knowledge in disaster management and adaptation development.

In Tanzania, increased variability of rainfall is challenging Indigenous and local communities(Mahoo et al., 2015; Sewando et al., 2016). The majority of agro-pastoralists use Indigenous knowledge to forecast seasonal rainfall, relying on observations of plant phenology, bird, animal, and insect behaviour, the sun and moon, and wind (Chang'a et al., 2010; Elia et al., 2014; Shaffer, 2014). Increased climate variability has raised concerns about the reliability of these indicators (Shaffer, 2014), therefore, initiatives have focused on the co-production of knowledge, through involving local communities in monitoring and discussing the implications of indigenous knowledge and meteorological forecasts (Shaffer, 2014), and creating local forecasts by utilising the two sources of knowledge (Mahoo et al., 2013). This has resulted in increased documentation of Indigenous knowledge, understanding of relevant climate information amongst stakeholders, and adaptive capacity at the community-level (Mahoo et al., 2013, 2015; Shaffer, 2014).

The Pacific Islands and Small Island Develiping States (SIDS) are vulnerable to the effects of climate change, but the cultural resilience of Pacific Island inhabitants is also recognized (Nunn et al., 2017). In Fiji and Vanuatu, strategies used to prepare for cyclones include building reserve emergency supplies, and utilising farming techniques to ensure adequate crop yield to combat potential losses from a cyclone or drought (McNamara and Prasad, 2014; Granderson, 2017; Pearce et al., 2017). Social cohesion and kinship are important in responding and preparing for climate-related hazards, including the role of resource sharing, communal labour, and remittances (McMillen et al., 2014; Gawith et al., 2016; Granderson, 2017). There is a concern that Indigenous knowledge will weaken, a process driven by westernisation and disruptions in established bioclimatic indicators and traditional planning calendars (Granderson, 2017). In some urban settlements, it has been noted that cultural practices (e.g., prioritising the quantity of food over the quality of food) can lower food security through dispersing limited resources and by encouraging the consumption of cheap but nutrient-poor foods (Mccubbin et al., 2017) (See Cross-Chapter Box 6 on Food Security in Chapter 3). Indigenous practices also encounter limitations, particularly in-relating to sea level rise (Nunn et al., 2017).

[END BOX 4.3 HERE]

[START BOX 4.4 HERE]

Box 4.4: Manizales, Colombia: Supportive National Government and Localised Planning and Integration as an Enabling Condition for Managing Climate and Development Risks

Institutional reform in the city of Manizales, Colombia helps identify three important features of an enabling environment: integrating climate change adaptation, mitigation and disaster risk management at the city-scale; the importance of decentralised planning and policy formulation within a supportive national policy environment; and the role of a multi-sectoral framework in mainstreaming climate action in development activities.

Manizales is exposed to risks caused by rapid development and expansion in a mountainous terrain exposed to seismic activity and periodic wet and dry spells. Local assessments expect climate change to amplify the risk of disasters (Carreño et al., 2017). The city is widely recognised for its longstanding urban environmental policy (Biomanizales) and local environmental action plan (Bioplan), and has been integrating environmental planning in its development agenda for nearly two decades (Velásquez Barrero, 1998; Hardoy and Velásquez Barrero, 2014). When the city's environmental agenda was updated in 2014 to reflect climate change risks, assessments were conducted in a participatory manner at the street and neighbourhood level (Hardoy and Velásquez Barrero, 2016).

The creation of a new Environmental Secretariat assisted in coordination and integration of environmental policies, disaster risk management, development and climate change (Leck and Roberts, 2015).
Planning in Manizales remains mindful of steep gradients, through its longstanding Slope Guardian

programme that trains women and keeps records of vulnerable households. Planning also looks to include mitigation opportunities and enhance local capacity through participatory engagement (Hardoy and Velásquez Barrero, 2016).

Manizales' mayors were identified as important champions for much of these early integration and innovation efforts. Their role may have been enabled by Colombia's history of decentralised approaches to planning and policy formulation, including establishing environmental observatories (for continuous environmental assessment) and participatory tracking of environmental indicators. Multi-stakeholder involvement has both enabled and driven progress, and has enabled the integration of climate risks in development planning (Hardoy and Velásquez Barrero, 2016).

[END BOX 4.4 HERE]

4.4.2.2 Monitoring, Reporting, and Review Institutions

One of the novel features of the new climate governance architecture emerging from the 2015 Paris Agreement is the transparency framework in Article 13 committing countries, based on capacity, to provide regular progress reports on national pledges to address climate change (UNFCCC, 2015). Many countries will rely on public policies and existing national reporting channels to deliver on their NDCs under the Paris Agreement. Scaling up the mitigation and adaptation efforts in these countries to be consistent with 1.5°C would put significant pressure on the need to develop, enhance and streamline local, national and international climate change reporting and monitoring methodologies and institutional capacity in relation to mitigation, adaptation, finance, and Greenhouse Gases (GHGs) inventories (Ford et al., 2015b; Lesnikowski et al., 2015; Schoenefeld et al., 2016). Consistent with this direction, the provision of the information to the stocktake under Article 14 of the Paris Agreement would contribute to enhancing reporting and transparency (UNFCCC, 2015). Nonetheless, approaches, reporting procedures, reference points, and data sources to assess progress on implementation across and within nations are still largely underdeveloped (Ford et al., 2015b; Araos et al., 2016b; Magnan and Ribera, 2016; Lesnikowski et al., 2017). The availability of independent private and public reporting and statistical institutions is integral to oversight, effective monitoring, reporting and review. The creation and enhancement of these institutions would be an important contribution to an effective transition to a low-emission world.

4.4.2.3 Financial Institutions

IPCC AR5 assessed that to enable a transition to a 2°C pathway, the volume of climate investments would need to be transformed along with changes in the pattern of general investment behaviour towards low-emissions. The report argued that, compared to 2012, annually up to a trillion dollars in additional investment in low-emission energy and energy efficiency measures may be required until 2050 (Blanco et al., 2014; IEA, 2014a). Financing of 1.5°C would present an even greater challenge, addressing financing of both existing and new assets, which would require significant transitions to the type and structure of financial institutions as well as to the method of financing (Cochrani et al., 2014; Ma, 2014). Both public and private financial institutions would be needed to contribute to the large resource mobilisation needed for 1.5°C, yet, in the ordinary course of business, these transitions may not be expected. On one hand, private financial institutions could face the scale-up risk, for example the risks associated with commercialisation and scaling up of renewable technologies to accelerate mitigation (Wilson, 2012; Hartley and Medlock, 2013) and/or price risk, such as carbon price volatility that carbon markets could face. In contrast, traditional public financial institutions are limited by both structure and instruments, while concessional financing would require taxpayer support for subsidisation. Special efforts and innovative approaches would be needed to address these challenges, for example the creation of special institutions that underwrite the value of emission reductions using auctioned price floors (Bodnar et al., 2018) to deal with price volatility.

Financial institutions are equally important for adaptation. Linnerooth-Bayer and Hochrainer-Stigler (2015) discuss the benefits of financial instruments in adaptation, including the provision of post-disaster finances for recovery and pre-disaster security necessary for climate adaptation and poverty reduction. Pre-disaster financial instruments and options include insurance, such as index-based weather insurance schemes, catastrophe bonds, and laws to encourage insurance purchasing. The development and enhancement of microfinance institutions to ensure social resilience and smooth transitions in the adaptation to climate change impacts could be an important local institutional innovation (Hammill et al., 2008).

4.4.2.4 Co-Operative Institutions and Social Safety Nets

Effective co-operative institutions and social safety nets may help address energy access, adaptation, as well as distributional impacts during the transition to 1.5°C-consistent pathways and enabling sustainable development. Not all countries have the institutional capabilities to design and manage these. Social capital for adaptation in the form of bonding, bridging, and linking social institutions has proved to be effective in dealing with climate crises at the local, regional, and national levels (Aldrich et al., 2016).

The shift towards sustainable energy systems in transitioning economies could impact the livelihoods of large populations, in traditional and legacy employment sectors. The transition of selected EU Member States to biofuels, for example, caused anxiety among farmers, who lacked confidence in the biofuel crop market. Enabling contracts between farmers and energy companies, involving local governments, helped create an atmosphere of confidence during the transition (McCormick and Kåberger, 2007).

How do broader socio-economic processes influence urban vulnerabilities and thereby underpin climate change adaptation? This is a systemic challenge originating from a lack of collective societal ownership of the responsibility for climate risk management. Numerous explanations, help explain this from competing time-horizons due to self-interest of stakeholders to a more 'rational' conception of risk assessment, measured across a risk-tolerance spectrum (Moffatt, 2014).

Self-governing and self-organised institutional settings where equipment and resource systems are commonly owned and managed can potentially generate a much higher diversity of administration solutions, than other institutional arrangements where energy technology and resource systems are either owned and administered individually in market settings or via a central authority (e.g., the state). They can also increase the adaptability of technological systems, while reducing their burden on the environment (Labanca, 2017). Educational, learning and awareness-building institutions can help strengthen the societal response to climate change (Butler et al., 2016; Thi Hong Phuong et al., 2017).

4.4.3 Enabling Lifestyle and Behavioural Change

Humans are at the centre of global climate change: their actions cause anthropogenic climate change, and social change is key to effectively respond to climate change (Vlek and Steg, 2007; Dietz et al., 2013; ISSC and UNESCO, 2013; Hackmann et al., 2014). Chapter 2 shows that 1.5°C-consistent pathways assume substantial changes in behaviour. This section assesses the potential of behaviour change, as the Integrated Assessment Models (IAMs) applied in Chapter 2 do not comprehensively asses this potential.

Table 4.8 shows examples of mitigation and adaption actions relevant for 1.5ºC-consistent pathways. Reductions in population growth can reduce overall carbon demand and mitigate climate change (Bridgeman, 2017), particularly when population growth is accompanied with increases in affluence and carbon-intensive consumption (Rosa and Dietz, 2012; Clayton et al., 2017). Mitigation actions with a substantial carbon emission reduction potential (see Figure 4.3) that individuals may readily adopt would have the most climate impact (Dietz et al., 2009).

Table 4.8: Examples of mitigation and adaptation behaviours relevant for 1.5ºC (Dietz et al., 2009; Jabeen, 2014; Taylor et al., 2014; Araos et al., 2016b; Steg, 2016; Stern et al., 2016b; Creutzig et al., 2018)

Climate action	Type of action	Examples
Mitigation	Implementing resource efficiency in building	Insulation Low-carbon building materials
	Adopting low-emission innovations	Electric vehicles Heat pumps, district heating and cooling
	Adopting energy efficient appliances	Energy-efficient heating or cooling Energy-efficient appliances
	Energy-saving behaviour	Walking or cycling rather than drive short distances Using mass transit rather than flying Lower temperature for space heating Line drying of laundry Reducing food waste
	Buying products and materials with low GHG emissions during production and transport	Reducing meat and dairy consumption Buying local, seasonal food Replacing aluminium products by low-GHG alternatives
	Organisational behaviour	Designing low-emission products and procedures Replacing business travel by videoconferencing
Adaptation	Growing different crops and raising different animal varieties	Using crops with higher tolerance for higher temperatures or CO_2 elevation
	Flood protective behaviour	Elevating barriers between rooms Building elevated storage spaces Building drainage channels outside the home
	Heat protective behaviour	Staying hydrated Moving to cooler places Installing green roofs
	Efficient water use during water shortage crisis	Rationing water Constructing wells or rainwater tanks
Mitigation & adaptation	Adoption of renewable energy sources	Solar PV Solar water heaters
	Citizenship behaviour	Engage through civic channels to encourage or support planning for low-carbon climate-resilient development

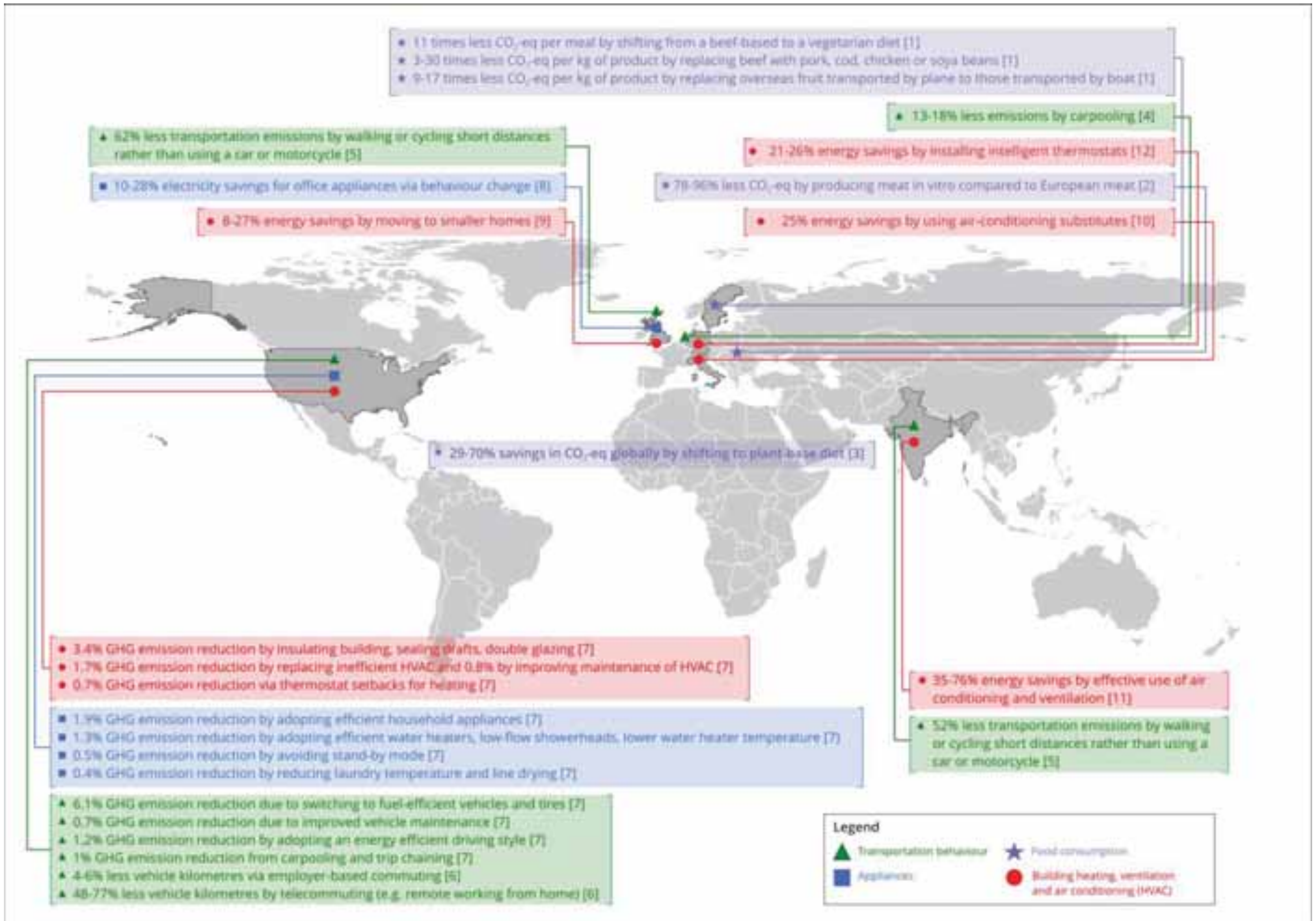


Figure 4.3: Examples of mitigation behaviour and their GHG emission reduction potential. Mitigation potential assessments are printed in different units. Based on [1] Carlsson-Kanyama and González (2009); [2] Tuomisto and Teixeira de Mattos (2011); [3] Springmann et al. (2016); [4] Nijland and Meerkerk (2017); [5] Woodcock et al. (2009); [6] Salon et al. (2012); [7] Dietz et al. (2009); [8] Mulville et al. (2017); [9] Huebner and Shipworth (2017); [10] Jaboyedoff et al. (2004); [11] Pellegrino et al. (2016); [12] Nägele et al. (2017).

Various policy approaches and strategies can encourage and enable climate actions by individuals and organisations. Policy approaches would be more effective when they address key contextual and psycho-social factors influencing climate actions, which differ across contexts and individuals (Steg and Vlek, 2009; Stern, 2011). This suggests that diverse policy approaches would be needed in 1.5ºC-consistent pathways in different contexts and regions. Combinations of policies that target multiple barriers and enabling factors simultaneously can be more effective (Nissinen et al., 2015).

In the US and Europe, GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon, 2011; Dietz et al., 2015). Political elites affect public concern about climate change: pro-climate action statements increased concern, while anti-climate action statements and anti-environment voting reduced public concern about climate change (Brulle et al., 2012). In the European Union, individuals worry more about climate change and engage more in climate actions in countries where political party elites are united rather than divided in their support for environmental issues (Sohlberg, 2017).

This section discusses how to enable and encourage behaviour and lifestyle changes that strengthen implementation of 1.5ºC-consistent pathways by assessing psycho-social factors related to climate action, as well as the effects and acceptability of policy approaches targeting climate actions that are consistent with 1.5ºC. Box 4.5 and Box 4.6 illustrate how these have worked in practice.

4.4.3.1 Factors Related to Climate Actions

Mitigation and adaptation behaviour is affected by many factors that shape which options are feasible and considered by individuals. Besides contextual factors (see other sub-sections in Section 4.4), these include abilities and different types of motivation to engage in behaviour.

4.4.3.1.1 Ability to engage in climate action

Individuals more often engage in adaptation (Gebrehiwot and van der Veen, 2015; Koerth et al., 2017) and mitigation behaviour (Pisano and Lubell, 2017) when they are or feel more capable to do so. Hence, it is important to enhance ability to act on climate change, which depends on income and knowledge, among other things. A higher income is related to higher CO_2 emissions; higher income groups can afford more carbon-intensive lifestyles (Lamb et al., 2014; Dietz et al., 2015; Wang et al., 2015). Yet, low-income groups may lack resources to invest in energy efficient technology and refurbishments (Andrews-Speed and Ma, 2016) and adaptation options (Wamsler, 2007; Fleming et al., 2015b; Takahashi et al., 2016). Adaptive capacity further depends on gender roles (Jabeen, 2014; Bunce and Ford, 2015), technical capacities and knowledge (Feola et al., 2015; Eakin et al., 2016; Singh et al., 2016b).

Knowledge of the causes and consequences of climate change and on ways to reduce GHG emissions is not always accurate (Bord et al., 2000; Whitmarsh et al., 2011; Tobler et al., 2012), which can inhibit climate actions, even when people would be motivated to act. For example, people overestimate savings from low-energy activities, and underestimate savings from high-energy activities (Attari et al., 2010). They know little about 'embodied' energy (i.e., energy needed to produce products; Tobler et al., 2011), including meat (de Boer et al., 2016b). Some people mistake weather for climate (Reynolds et al., 2010), or conflate climate risks with other hazards, which can inhibit adequate adaptation (Taylor et al., 2014).

More knowledge on adaptation is related to higher engagement in adaptation actions in some circumstances (Bates et al., 2009; van Kasteren, 2014; Hagen et al., 2016). How adaptation is framed in the media can influence the types of options viewed as important in different contexts (Boykoff et al., 2013; Moser, 2014; Ford and King, 2015).

Knowledge is important, but is often not sufficient to motivate action (Trenberth et al., 2016). Climate change knowledge and perceptions are not strongly related to mitigation actions (Hornsey et al., 2016). Direct experience of events related to climate change influences climate concerns and actions (Blennow et al., 2012; Taylor et al., 2014), more so than second-hand information (Spence et al., 2011; Myers et al., 2012; Demski et al., 2017); high impact events with low frequency are remembered more than low impact regular events (Meze-Hausken, 2004; Singh et al., 2016b; Sullivan-Wiley and Short Gianotti, 2017). Personal experience with climate hazards strengthens motivation to protect oneself (Jabeen, 2014) and enhances adaptation actions (Bryan et al., 2009; Berrang-Ford et al., 2011; Demski et al., 2017), although this does not always translate into proactive adaptation (Taylor et al., 2014). Collectively constructed notions of risk and expectations of future climate variability shape risk perception and adaptation behaviour (Singh et al., 2016b). People with particular political views and those who emphasise individual autonomy may reject climate science knowledge and believe that there is widespread scientific disagreement about climate change (Kahan, 2010; O'Neill et al., 2013), inhibiting support for climate policy (Ding et al., 2011; McCright et al., 2013). This may explain why extreme weather experiences enhances preparedness to reduce energy use among left- but not right-leaning voters (Ogunbode et al., 2017).

4.4.3.1.2 Motivation to engage in climate action

Climate actions are more strongly related to motivational factors, reflecting individuals' reasons for actions, such as values, ideology and worldviews than to knowledge (Hornsey et al., 2016). People consider various types of costs and benefits of actions (Gölz and Hahnel, 2016), and focus on consequences that have implications for the values they find most important (Dietz et al., 2013; Hahnel et al., 2015; Steg, 2016). This implies that different individuals consider different consequences when making choices. People who strongly value protecting the environment and other people generally more strongly consider climate impact and act more on climate change than those who strongly endorse hedonic and egoistic values (Taylor et al., 2014; Steg, 2016). People are more prone to adopt sustainable innovations when they are more open to new ideas (Jansson, 2011; Wolske et al., 2017). Further, a free-market ideology is associated with weaker climate change beliefs (McCright and Dunlap, 2011; Hornsey et al., 2016), and a capital-oriented culture tends to promote activity associated with GHG emissions (Kasser et al., 2007).

Some Indigenous populations believe it is arrogant to predict the future, and some cultures have belief systems that interpret natural phenomena as sentient, where thoughts and words are believed to influence the future, with people reluctant to talk about negative future possibilities (Natcher et al., 2007; Flynn et al., 2018). Integrating these considerations into the design of adaptation and mitigation policy is important (Cochran et al., 2013; Chapin et al., 2016; Brugnach et al., 2017; Flynn et al., 2018).

People are more prone to act on climate change when individual benefits of actions exceed costs (Steg and Vlek, 2009; Kardooni et al., 2016; Wolske et al., 2017). For this reason, people generally prefer adoption of energy-efficient appliances above energy consumption reductions; the latter is perceived as more costly (Poortinga et al., 2003; Steg et al., 2006), although transaction costs can inhibit the uptake of mitigation technology (Mundaca, 2007). Decentralised renewable energy systems are evaluated most favourably when they guarantee independence, autonomy, control and supply security (Ecker, 2017).

Besides, social costs and benefits affect climate action (Farrow et al., 2017). People engage more in climate actions when they think others expect them to do so and when others act as well (Nolan et al., 2008; Le Dang et al., 2014; Truelove et al., 2015; Rai et al., 2016), and when they experience social support (Singh et al., 2016a; Burnham and Ma, 2017; Wolske et al., 2017). Discussing effective actions with peers also encourages climate action (Esham and Garforth, 2013), particularly when individuals strongly identify with their peers (Biddau et al., 2012; Fielding and Hornsey, 2016). Further, individuals may engage in mitigation actions when they think doing so would enhance their reputation (Milinski et al., 2006; Noppers et al., 2014; Kastner and Stern, 2015). Such social costs and benefits can be addressed in climate policy (see Section 4.4.3.2).

Feelings affect climate action (Brosch et al., 2014). Negative feelings related to climate change can encourage adaptation action (Kerstholt et al., 2017; Zhang et al., 2017), while positive feelings associated with climate risks may inhibit protective behaviour (Lefevre et al., 2015). Individuals are more prone to engage in mitigation actions when they worry about climate change (Verplanken and Roy, 2013), and when they expect to derive positive feelings from such actions (Pelletier et al., 1998; Taufik et al., 2016).

Furthermore, collective consequences affect climate actions (Balcombe et al., 2013; Dóci and Vasileiadou, 2015; Kastner and Stern, 2015). People are motivated to see themselves as morally right, which encourages mitigation actions (Steg et al., 2015), particularly when long-term goals are salient (Zaval et al., 2015) and behavioural costs are not too high (Diekmann and Preisendörfer, 2003). Individuals are more prone to engage in climate actions when they believe climate change is occurring, when they are aware of threats caused by climate change and by their inaction, and when they think they can engage in actions that will reduce these threats (Esham and Garforth, 2013; Arunrat et al., 2017; Chatrchyan et al., 2017). The more individuals are concerned about climate change and aware of the negative climate impact of their behaviour, the more they feel responsible for and think their actions can help reduce such negative impacts, which can strengthen their moral norms to act accordingly (Steg and de Groot, 2010; Jakovcevic and Steg, 2013; Chen, 2015; Ray et al., 2017; Wolske et al., 2017; Woods et al., 2017). Individuals may engage in mitigation actions when they see themselves as supportive of the environment (i.e. strong environmental self-identity) (Fielding et al., 2008; van der Werff et al., 2013b; Kashima et al., 2014; Barbarossa et al., 2017); a strong environmental identity strengthens intrinsic motivation to engage in mitigation actions both at home (van der Werff et al., 2013a) and at work (Ruepert et al., 2016). Environmental self-identity is strengthened when people realise they engaged in mitigation actions, which can in turn promote further mitigation actions (van der Werff et al., 2014b).

Individuals are less prone to engage in adaptation behaviour themselves when they rely on external measures such as government interventions (Grothmann and Reusswig, 2006; Wamsler and Brink, 2014a; Armah et al., 2015; Burnham and Ma, 2017) or perceive themselves as protected by god (Gandure et al., 2013; Dang et al., 2014; Cannon, 2015).

4.4.3.1.3 Habits, heuristics and biases

Decisions are often not based on weighing costs and benefits, but on habit or automaticity, both of individuals (Aarts and Dijksterhuis, 2000; Kloeckner et al., 2003) and within organisations (Dooley, 2017) and institutions (Munck et al., 2014). When habits are strong, individuals are less perceptive of information (Verplanken et al., 1997; Aarts et al., 1998), and may not consider alternatives as long as outcomes are good enough (Maréchal, 2010). Habits are mostly only reconsidered when the situation changed significantly (Fujii and Kitamura, 2003; Maréchal, 2010; Verplanken and Roy, 2016). Hence, strategies that create the opportunity for reflection and encourage active decisions can break habits (Steg et al., 2017).

Individuals can follow heuristics, or 'rules of thumb', in making inferences rather than thinking through all implications of actions, which demands less cognitive resources, knowledge and time (Preston et al., 2013; Frederiks et al., 2015; Gillingham and Palmer, 2017). For example, people tend to think that larger and visible appliances use more energy, which is not always accurate (Cowen and Gatersleben, 2017). They underestimate energy used for water heating and overestimate energy used for lighting (Stern, 2014). When facing choice overload, people may choose the easiest or first available option, which can inhibit energy saving behaviour (Stern and Gardner, 1981; Frederiks et al., 2015). As a result, individuals and firms often strive for satisficing ('good enough') outcomes with regard to energy decisions (Wilson and Dowlatabadi, 2007; Klotz, 2011), which can inhibit investments in energy efficiency (Decanio, 1993; Frederiks et al., 2015).

Besides, biases play a role. In Mozambique, farmers displayed omission biases (unwillingness to take adaptation actions with potentially negative consequences to avoid personal responsibility for losses), while policymakers displayed action biases (wanting to demonstrate positive action despite potential negative consequences; Patt and Schröter, 2008). People tend to place greater value on relative losses than gains (Kahneman, 2003). Perceived gains and losses depend on the reference point or status-quo (Kahneman, 2003). Loss aversion and the status-quo bias prevent consumers from switching electricity suppliers (Ek and Söderholm, 2008), to time-of-use electricity tariffs (Nicolson et al., 2017), and to accept new energy systems (Leijten et al., 2014).

Owned inefficient appliances and fossil fuel-based electricity can act as endowments, increasing their value compared to alternatives (Pichert and Katsikopoulos, 2008; Dinner et al., 2011). Uncertainty and loss aversion lead consumers to undervalue future energy savings (Greene, 2011) and savings from energy efficient technologies (Kolstad et al., 2014). Uncertainties about the performance of products and illiquidity of investments can drive consumers to postpone (profitable) energy efficient investments (Sutherland, 1991; van Soest and Bulte, 2001). People with a higher tendency to delay decisions may engage less in energy saving actions (Lillemo, 2014). Training energy auditors in loss-aversion increased their clients' investments in energy efficiency improvements (Gonzales et al., 1988). Engagement in energy saving and renewable energy programmes can be enhanced if participation is set as a default option (Pichert and Katsikopoulos, 2008; Ölander and Thøgersen, 2014; Ebeling and Lotz, 2015).

4.4.3.2 Strategies and Policies to Promote Actions on Climate Change

Policy can enable and strengthen motivation to act on climate change via top-down or bottom-up approaches, through informational campaigns, regulatory measures, financial (dis)incentives, and infrastructural and technological changes (Adger et al., 2003; Steg and Vlek, 2009; Henstra, 2016).

Adaptation efforts tend to focus on infrastructural and technological solutions (Ford and King, 2015) with lower emphasis on socio-cognitive and finance aspects of adaptation. For example, flooding policies in cities focus on infrastructure projects and regulation such as building codes, and hardly target individual or household behaviour (Araos et al., 2016b; Georgeson et al., 2016).

Current mitigation policies emphasise infrastructural and technology development, regulation, financial incentives and information provision (Mundaca and Markandya, 2016) that can create conditions enabling climate action, but target only some of the many factors influencing climate actions (see Section 4.4.5.1). They fall short of their true potential if their social and psychological implications are overlooked (Stern et al., 2016a). For example, promising energy-saving or low carbon technology may not be adopted or not be used as intended (Pritoni et al., 2015) when people lack resources and trustworthy information (Stern, 2011; Balcombe et al., 2013).

Financial incentives or feedback on financial savings can encourage climate action (Santos, 2008; Bolderdijk et al., 2011; Maki et al., 2016) (see Box 4.5), but are not always effective (Delmas et al., 2013), and can be less effective than social rewards (Handgraaf et al., 2013) or emphasising benefits for people and the environment (Bolderdijk et al., 2013b; Asensio and Delmas, 2015; Schwartz et al., 2015). The latter can happen when financial incentives reduce a focus on environmental considerations and weaken intrinsic motivation to engage in climate action (Evans et al., 2012; Agrawal et al., 2015; Schwartz et al., 2015). Besides, pursuing small financial gains is perceived to be less worth the effort than pursuing equivalent CO_2 emission reductions (Bolderdijk et al., 2013b; Dogan et al., 2014). Also, people may not respond to financial incentives (e.g., to improve energy efficiency) because they do not trust the organisation sponsoring incentive programmes (Mundaca, 2007) or when it takes too much effort to receive the incentive (Stern et al., 2016a).

[START BOX 4.5 HERE]

Box 4.5: How Pricing Policy has Reduced Car Use in Singapore, Stockholm and London

In Singapore, Stockholm and London, car ownership, car use, and Greenhouse Gas (GHG) emissions have reduced because of pricing and regulatory policies and policies facilitating behaviour change. Notably, acceptability of these policies has increased as people experienced their positive effects.

Singapore implemented electronic road pricing in the central business district and at major expressways, a vehicle quota and registration fee system, and investments in mass transit. In the vehicle quota system introduced in 1990, registration of new vehicles is conditional upon a successful bid (via auctioning) (Chu, 2015), costing about 50,000 USD in 2014 (LTA, 2015). The registration tax incentivises purchases of low-emission vehicles via a feebate system. As a result, per capita transport emissions (approximately 1.25 tCO_2/yr^{-1}) and car ownership (107 vehicles per 1000 capita) (LTA, 2017) are substantially lower than in cities with comparable income levels. Modal share of public transport was 63% during peak hours in 2013 (LTA, 2013).

The Stockholm congestion charge implemented in 2007 (after a trial in 2006) reduced kilometres driven in the inner city by 16%, and outside the city by 5%; traffic volumes reduced by 20% and remained constant across time despite economic and population growth (Eliasson, 2014). CO_2 emissions from traffic reduced by 2–3% in Stockholm county. Vehicles entering or leaving the city centre were charged during weekdays (except for holidays). Charges were 1–2€ (maximum 6€ per day), being higher during peak hours; taxis, emergency vehicles and busses were exempted. Before introducing the charge, public transport and parking places near mass transit stations were extended. The aim and effects of the charge were extensively communicated to the public. Acceptability of the congestion charge was initially low, but gained support of about two-thirds of the population and all political parties after the scheme was implemented (Eliasson, 2014), which may be related to earmarking the revenues to constructing a motorway tunnel. After the trial, people believed that the charge had more positive effects on environmental, congestion and parking problems while costs increased less than they anticipated beforehand (Schuitema et al., 2010a). The initially hostile media eventually declared the scheme to be a success.

In 2003, a congestion charge was implemented in the Greater London area, with an enforcement and compliance scheme and an information campaign on the functioning of the scheme. Vehicles entering, leaving, driving or parking on a public road in the zone at weekdays at daytime pay a congestion charge of 8£ (until 2005 5£), with some exemptions. Revenues were invested in London's bus network (80%), cycling facilities, and road safety measures (Leape, 2006). The number of cars entering the zone decreased by 18% in 2003 and 2004. In the charging zone, vehicle kilometres driven decreased by 15% in the first year and a further 6% a year later, while CO_2 emissions from road traffic reduced by 20% (Santos, 2008).

[END BOX 4.5 HERE]

While providing information on the causes and consequences of climate change or on effective climate actions, generally increases knowledge, it often does not encourage engagement in climate actions by individuals (Abrahamse et al., 2005; Ünal et al., 2017) or organisations (Anderson and Newell, 2004). Similarly, media coverage on the UN Climate Summit slightly increased knowledge about the conference but did not enhance motivation to engage personally in climate protection (Brüggemann et al., 2017). Fear-inducing representations of climate change may inhibit action when they make people feel helpless and overwhelmed (O'Neill and Nicholson-Cole, 2009). Energy-related recommendations and feedback (e.g., via performance contracts, energy audits, smart metering) are more effective to promote energy conservation, load shifting in electricity use and sustainable travel choices when framed in terms of losses rather than gains (Gonzales et al., 1988; Wolak, 2011; Bradley et al., 2016; Bager and Mundaca, 2017).

Credible and targeted information at the point of decision can promote climate action (Stern et al., 2016a). For example, communicating the impacts of climate change is more effective when provided right before adaptation decisions are taken (e.g., before the agricultural season) and when bundled with information on potential actions to ameliorate impacts, rather than just providing information on climate projections with little meaning to end users (e.g., weather forecasts, seasonal forecasts, decadal climate trends) (Dorward et al., 2015; Singh et al., 2017). Similarly, heat action plans that provide early alerts and advisories combined with emergency public health measures can reduce heat-related morbidity and mortality (Benmarhnia et al., 2016).

Information provision is more effective when tailored to the personal situation of individuals, demonstrating clear impacts, and resonating with individuals' core values (Daamen et al., 2001; Abrahamse et al., 2007; Bolderdijk et al., 2013a; Dorward et al., 2015; Singh et al., 2017). Tailored information prevents information overload, and people are more motivated to consider and act upon information that aligns with their core values and beliefs (Campbell and Kay, 2014; Hornsey et al., 2016). Also, tailored information can remove barriers to receive and interpret information faced by vulnerable groups, such as the elderly during heat waves (Vandentorren et al., 2006; Keim, 2008). Further, prompts can be effective when they serve as reminders to perform a planned action (Osbaldiston and Schott, 2012).

Feedback provision is generally effective in promoting mitigation behaviour within households (Abrahamse et al., 2005; Delmas et al., 2013; Karlin et al., 2015) and at work (Young et al., 2015), particularly when provided in real-time or immediately after the action (Abrahamse et al., 2005), which makes the implications of one's behaviour more salient (Tiefenbeck et al., 2016). Simple information is more effective than detailed and technical data (Wilson and Dowlatabadi, 2007; Ek and Söderholm, 2010; Frederiks et al., 2015). Energy labels (Banerjee and Solomon, 2003; Stadelmann, 2017), visualisation techniques (Pahl et al., 2016), and ambient persuasive technology (Midden and Ham, 2012) can encourage mitigation actions by providing information and feedback in a format that immediately makes sense and hardly requires users' conscious attention.

Social influence approaches that emphasise what other people do or think can encourage climate action (Clayton et al., 2015), particularly when they involve face-to-face interaction (Abrahamse and Steg, 2013). For example, community approaches, where change is initiated from the bottom-up, can promote adaptation (see Box 4.6) and mitigation actions (Middlemiss, 2011; Seyfang and Haxeltine, 2012; Abrahamse and Steg, 2013), especially when community ties are strong (Weenig and Midden, 1991). Furthermore, providing social models of desired actions can encourage mitigation action (Osbaldiston and Schott, 2012; Abrahamse and Steg, 2013). Social influence approaches that do not involve social interaction, such as social norm, social comparison and group feedback, are less effective, but can be easily administered on a large scale at low costs (Allcott, 2011; Abrahamse and Steg, 2013).

[START BOX 4.6 HERE]

Box 4.6: Bottom-up Initiatives: Adaptation Responses Initiated by Individuals and Communities

To effectively adapt to climate change, bottom-up initiatives by individuals and communities are essential, in addition to efforts of governments, organisations, and institutions (Wamsler and Brink, 2014a). This box presents examples of bottom-up adaptation responses and behavioural change.

Fiji increasingly faces a lack of freshwater due to decreasing rainfall and rising temperatures (Deo, 2011; IPCC, 2014a). While some villages have access to boreholes, these are not sufficient to supply the population with freshwater. Villagers are adapting by rationing water, changing diets, and setting up inter-village sharing networks (Pearce et al., 2017). Some villagers take up wage employment to buy food instead of growing it themselves (Pearce et al., 2017). In Kiribati, residents adapt to drought by purchasing rainwater tanks and constructing additional wells (Kuruppu and Liverman, 2011). An important factor that motivated residents of Kiribati to adapt to drought was the perception that they could effectively adapt to the negative consequences of climate change (Kuruppu and Liverman, 2011).

In the Philippines, seismic activity has caused some islands to flood during high tide. While the municipal government offered affected island communities the possibility to relocate to the mainland, residents preferred to stay and implement measures themselves in their local community to reduce flood damage (Laurice Jamero et al., 2017). Migration is perceived as undesirable because island communities have strong place-based identities (Mortreux and Barnett, 2009), Instead, these island communities have adapted to flooding by constructing stilted houses and raising floors, furniture, and roads to prevent water damage (Laurice Jamero et al., 2017). While inundation was in this case caused by seismic activity, this example indicates how island-based communities may respond to rising sea levels caused by climate change.

Adaptation initiatives by individuals may temporarily reduce the impacts of climate change and enable residents to cope with changing environmental circumstances. However, they may not be sufficient to sustain communities' way of life in the long term. For instance, in Fiji and Kiribati, freshwater and food are projected to become even scarcer in the future, rendering individual adaptations ineffective. Moreover, individuals can sometimes engage in behaviour that may be maladaptive over larger spatio-temporal scales. For example, in the Philippines, many islanders adapt to flooding by elevating their floors using coral stone (Laurice Jamero et al., 2017). Over time, this can harm the survivability of their community, as coral reefs are critical for reducing flood vulnerability (Ferrario et al., 2014). In Maharashtra, India, on-farm ponds are promoted as rainwater harvesting structures to adapt to dry spells during the monsoon season. However, some individuals fill these ponds with groundwater, leading to depletion of water tables and potentially maladaptive outcomes in the long run (Kale, 2015).

Integration of individuals' adaptation initiatives with top-down adaptation policy is critical (Butler et al., 2015), as failing to do so may lead individual actors to mistrust authority and can discourage them from undertaking adequate adaptive actions (Wamsler and Brink, 2014a).

[END BOX 4.6 HERE]

Goal setting can promote mitigation action, when goals are not set too low or too high (Loock et al., 2013). Commitment strategies where people make a pledge to engage in climate actions can encourage mitigation behaviour (Abrahamse and Steg, 2013; Lokhorst et al., 2013), particularly when individuals also indicate how and when they will perform the relevant action and anticipate how to cope with possible barriers (i.e., implementation intentions) (Bamberg, 2000, 2002). Such strategies take advantage of individuals' desire to be consistent (Steg, 2016). Similarly, hypocrisy strategies that make people aware of inconsistencies between their attitudes and behaviour can encourage mitigation actions (Osbaldiston and Schott, 2012).

Actions that reduce climate risks can be rewarded and facilitated, while actions that increase climate risks can be punished and inhibited, and behaviour change can be voluntary (e.g., information provision) or imposed (e.g., by law); voluntary changes that involve rewards are more acceptable than imposed changes that restrict choices (Eriksson et al., 2006, 2008; Steg et al., 2006; Dietz et al., 2007). Policies punishing maladaptive behaviour can increase vulnerability when they reinforce socio-economic inequalities that typically produce the maladaptive behaviour in the first place (W.N. Adger et al., 2003). Change can be initiated by governments at various levels, but also by individuals, communities, profit-making organisations, trade organisations, and other non-governmental actors (Lindenberg and Steg, 2013; Robertson and Barling, 2015; Stern et al., 2016b).

Strategies can target intrinsic versus extrinsic motivation. It may be particularly important to enhance intrinsic motivation so that people voluntarily engage in climate action over and again (Steg, 2016). Endorsement of mitigation and adaptation actions are positively related (Brügger et al., 2015; Carrico et al., 2015); both are positively related to concern about climate change (Brügger et al., 2015). Strategies that target general antecedents that affect a wide range of actions, such as values, identities, worldviews, climate change beliefs, awareness of climate impacts of one's actions and feelings of responsibility to act on climate change, can encourage consistent actions on climate change (van Der Werff and Steg, 2015; Hornsey et al., 2016; Steg, 2016). Initial climate actions can lead to further commitment to climate action (Juhl et al., 2017), when people learn that such actions are easy and effective (Lauren et al., 2016), when they engaged in the initial behaviour for environmental reasons (Peters et al., 2018), hold strong pro-environmental values and norms (Thøgersen, J., Ölander, 2003), and when initial actions make them realise they are an environmentally-sensitive person, motivating them to act on climate change in subsequent situations so as to be consistent (van der Werff et al., 2014a; Lacasse, 2015, 2016). Yet, some studies suggest that people may feel licensed not to engage in further mitigation actions when they believe they already did their bit (Truelove et al., 2014).

4.4.3.3 Acceptability of Policy and System Changes

Public acceptability can shape, enable or prevent policy and system changes. Acceptability reflects the extent to which policy or system changes are evaluated (un)favourably. Acceptability is higher when people expect more positive and less negative effects of policy and system changes (Perlaviciute and Steg, 2014; Demski et al., 2015; Drews and Van den Bergh, 2016), including climate impacts (Schuitema et al., 2010b). Because of this, policy 'rewarding' climate actions is more acceptable than policy 'punishing' actions that increase climate risks (Steg et al., 2006; Eriksson et al., 2008). Pricing policy is more acceptable when revenues are earmarked for environmental purposes (Steg et al., 2006; Sælen and Kallbekken, 2011), or redistributed towards those affected (Schuitema and Steg, 2008). Acceptability can increase when people experience positive effects after a policy has been implemented (Schuitema et al., 2010a; Eliasson, 2014; Weber, 2015); effective policy trials can thus build public support for climate policy.

Climate policy and renewable energy systems are more acceptable when people strongly value other people and the environment, or support egalitarian worldviews, left-wing or green political ideologies (Drews and Van den Bergh, 2016), and less acceptable when people strongly endorse self-enhancement values, or support individualistic and hierarchical worldviews (Dietz et al., 2007; Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Solar radiation modification is more acceptable when people strongly endorse self-enhancement values, and less acceptable when they strongly value other people and the environment (Visschers et al., 2017). Climate policy is more acceptable when people believe climate change is real, when they are concerned about climate change (Hornsey et al., 2016), when they think their actions may reduce climate risks, and when they feel responsible to act on climate change (Steg et al., 2005; Eriksson et al., 2006; Jakovcevic and Steg, 2013; Drews and Van den Bergh, 2016; Kim and Shin, 2017). Stronger environmental awareness is associated with a preference for governmental regulation and behaviour change, rather than free market and technological solutions (Poortinga et al., 2002).

Climate policy is more acceptable when costs and benefits are distributed equally, when nature and future generations are protected (Sjöberg and Drottz-Sjöberg, 2001; Schuitema et al., 2011; Drews and Van den Bergh, 2016), and when fair procedures have been followed, including participation by the public (Dietz, 2013; Bernauer et al., 2016a; Bidwell, 2016) or public society organisations (Bernauer and Gampfer, 2013). Providing benefits to compensate affected communities for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg, 2014), although people may disagree on what would be a worthwhile compensation (Aitken, 2010; Cass et al., 2010), or feel they are being bribed (Cass et al., 2010; Perlaviciute and Steg, 2014).

Public support is higher when individuals trust responsible parties (Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Yet, public support for multilateral climate policy is not higher than for unilateral policy (Bernauer and Gampfer, 2015); public support for unilateral, non-reciprocal climate policy is rather strong and robust (Bernauer et al., 2016b). Public opposition may result from a culturally valued landscape being affected by adaptation or mitigation options, such as renewable energy development (Warren et al., 2005; Devine-wright and Howes, 2010) or coastal protection measures (Kimura, 2016), particularly when people have formed strong emotional bonds with the place (Devine-Wright, 2009, 2013).

Climate actions may reduce human wellbeing when such actions involve more costs, effort or discomfort. Yet, some climate actions enhance wellbeing, such as technology that improves daily comfort and nature-based solutions for climate adaptation (Wamsler and Brink, 2014b). Further, climate action may enhance wellbeing (Kasser and Sheldon, 2002; Xiao et al., 2011; Schmitt et al., 2018) because pursuing meaning by acting on climate change can make people feel good (Venhoeven et al., 2013, 2016; Taufik et al., 2015), more so than merely pursuing pleasure.

4.4.4 Enabling Technological Innovation

This section focuses on the role of technological innovation in limiting warming to 1.5ºC, and how innovation can contribute to strengthening implementation to move towards or to adapt to 1.5ºC worlds. This assessment builds on information of technological innovation and related policy debates in and after AR5 (Somanathan et al., 2014).

4.4.4.1 The Nature of Technological Innovations

Technological systems have their own dynamics. New technologies have been described as emerging as part of a ‘socio-technical system’ that is integrated with social structures and that itself evolves over time (Geels and Schot, 2007). This progress is cumulative and accelerating (Kauffman, 2002; Arthur, 2009). To illustrate such a process of co-evolution: the progress of computer simulation enables us to understand climate, agriculture, and material sciences better, contributing to upgrading food production and quality, microscale manufacturing techniques, and leading to much faster computing technologies, resulting for instance in better performing Photovoltaic (PV) cells.

A variety of technological developments have and will, contribute to 1.5°C-consistent climate action or the lack of it. They can do this, e.g., in the form of applications such as smart lighting systems, more efficient drilling techniques making fossil fuels cheaper, or precision agriculture. As discussed in Section 4.3.1, costs of PV (IEA, 2017f) and batteries (Nykvist and Nilsson, 2015) have sharply dropped. In addition, costs of fuel cells (Iguma and Kidoshi, 2015; Wei et al., 2017) and shale gas and oil (Wang et al., 2014; Mills, 2015) have come down as a consequence of innovation.

4.4.4.2 Technologies as Enablers of Climate Action

Since AR5, literature has emerged as to how much future GHG emission reductions can be enabled by the rapid progress of General Purpose Technologies (GPTs), consisting of Information and Communication Technologies (ICT) including Artificial Intelligence (AI) and Internet-of-Things (IoT), nanotechnologies, biotechnologies, robotics, and so forth (World Economic Forum, 2015; OECD, 2017c). Although these may contribute to limiting warming to 1.5°C, the potential environmental, social and economic impacts of new technologies are uncertain.

Rapid improvement of performance and cost reduction is observed for many GPTs. They include AI, sensors, internet, memory storage and micro-electro mechanical systems. The latter GPTs are not usually categorised as climate technologies, but they can impact GHG emissions.

Progress of GPT could help reducing GHG emissions more cost-effectively. Examples are shown in Table 4.9. It may however, result in more emissions by increasing the volume of economic activities, with unintended negative consequence on sustainable development. While ICT increases electricity consumption (Aebischer and Hilty, 2015), the energy consumption of ICT is usually dwarfed by the energy saving by ICT (Koomey et al., 2013; Malmodin et al., 2014), but rebound effects and other sustainable development impacts may be significant. An appropriate policy framework that accommodates such impacts and their uncertainties could address the potential negative impacts by GPT (Jasanoff, 2007).

GHG emission reduction potentials in relation to GPTs were estimated for passenger cars using a combination of three emerging technologies: electric vehicles, car sharing, and self-driving. GHG emission reduction potential is reported, assuming generation of electricity with low GHG emissions (Greenblatt and Saxena, 2015; ITF, 2015; Viegas et al., 2016; Fulton et al., 2017). It is also possible that GHG emissions increase due to an incentive to car use. Appropriate policies such as urban planning and efficiency regulations could contain such rebound effects (Wadud et al., 2016).

Estimating emission reductions by GPT is difficult due to substantial uncertainties, including projections of future technological performance, costs, penetration rates, and induced human activity. Even if a technology is available, the establishment of business models might not be feasible (Linder and Williander, 2017). Indeed, studies show a wide range of estimates, ranging from deep emission reductions to possible increases in the emissions due to the rebound effect (Larson and Zhao, 2017).

GPT could also enable climate adaptation, in particular through more effective climate disaster risk management and improved weather forecasting.

Table 4.9: Examples of technological innovations relevant to 1.5°C enabled by General Purpose Technologies (GPT). Note: Lists of enabling GPT or adaptation/mitigation options are not exhaustive, and the GPTs by themselves do not reduce emissions or increase climate change resilience.

Sector	Examples of mitigation/adaptation technological innovation	Enabling GPT
Buildings	Energy and CO_2 efficiency of logistics, warehouse and shops (GeSI, 2015; IEA, 2017a)	IoT, AI
	Smart lighting and air conditioning (IEA, 2016b, 2017a)	IoT, AI, nanotechnology
Industry	Energy efficiency improvement by industrial process optimisation (IEA, 2017a)	Robots, IoT
	Bio-based plastic production by bio-refinery (OECD, 2017c)	Biotechnology
	New materials from bio-refineries (Fornell et al., 2013; McKay et al., 2016)	ICT, Biotechnology
Transport	Electric vehicles, car sharing, automation (Greenblatt and Saxena, 2015; Fulton et al., 2017)	IoT, AI, nanotechnology
	Bio-based diesel fuel by bio-refinery (OECD, 2017c)	Biotechnology
	Second Generation Bioethanol potentially coupled to Carbon Capture Systems (de Souza et al., 2014; Rochedo et al., 2016)	ICT, Biotechnology
	Logistical optimisation, and electrification of trucks by overhead line (IEA, 2017e)	IoT, AI
	Reduction of transport needs by remote education, health, and other services (GeSI, 2015; IEA, 2017a)	ICT
	Energy saving by lightweight aircraft components (Beyer, 2014; Faludi et al., 2015; Verhoef et al., 2018)	Additive manufacturing (3D printing)
Electricity	Solar PV manufacturing (Nemet, 2014)	Nanotechnology
	Smart grids and grid flexibility to accommodate intermittent renewables (Heard et al., 2017)	IoT, AI
	Plasma confinement for nuclear fusion (Baltz et al., 2017)	AI
Agriculture	Precision agriculture (improvement of energy and resource efficiency including reduction of fertiliser use and N_2O emissions) (Pierpaoli et al., 2013; Brown et al., 2016; Schimmelpfennig and Ebel, 2016)	Biotechnology ICT, AI
	Methane inhibitors (methanogenic vaccines) that reduce dairy livestock emissions (Wollenberg et al., 2016)	Biotechnology
	Engineering C3 into C4 photosynthesis to improve agricultural production and productivity (Schuler et al., 2016)	Biotechnology
	Genome editing using CRISPR to improve/adapt crops to a changing climate (Gao, 2018)	Biotechnology
Disaster reduction and adaptation	Weather forecasting and early warning systems, in combination with user knowledge (Hewitt et al., 2012; Lourenço et al., 2016)	ICT
	Climate risk reduction (Upadhyay and Bijalwan, 2015)	ICT
	Rapid assessment of disaster damage (Kryvasheyeu et al., 2016)	ICT

Government policy usually plays a role in promoting or limiting GPTs, or science and technology in general. It has impacts on climate action, because the performance of further climate technologies will partly depend on the progress of GPTs. Governments have established institutions for achieving many social, and sometimes conflicting goals, including economic growth and addressing climate change (OECD, 2017c), which include investment in basic R&D that can help develop game changing technologies (Shayegh et al., 2017). Governments are also needed to create an enabling environment for the growth of scientific and technological ecosystems necessary for GPT development (Tassey, 2014).

4.4.4.3 The Role of Government in 1.5°C-Consistent Climate Technology Policy

While literature on 1.5°C-specific innovation policy is absent, a growing body of literature indicates that governments aim to achieve social, economic and environmental goals by promoting science and a broad range of technologies through 'mission-driven' innovation policies, based on differentiated national priorities

(Edler and Fagerberg, 2017). Governments can play a role in advancing climate technology via a 'technology push' policy on the technology supply side (e.g., R&D subsidies), and by 'demand pull' policy on the demand side (e.g., energy efficiency regulation), and these policies can be complemented by enabling environments (Somanathan et al., 2014). Governments may also play a role in removing existent support for incumbents (Kivimaa and Kern, 2016). A growing literature indicates that policy mixes, rather than single policy instruments, are more effective in addressing climate innovation challenges ranging from technologies in the R&D phase to those ready for diffusion (Veugelers, 2012; Quitzow, 2015; Rogge et al., 2017; Rosenow et al., 2017). Such innovation policies can help address two kinds of externalities: environmental externalities and proprietary problems (GEA, 2012; IPCC, 2014b; Mazzucato and Semieniuk, 2017). To avoid 'picking winners', governments often maintain a broad portfolio of technological options (Kverndokk and Rosendahl, 2007) and work in close collaboration with the industrial sector and society in general. Some governments have achieved relative success in supporting innovation policies (Grubler et al., 2012; Mazzucato, 2013) that addressed climate-related R&D (see Box 4.7 on bioethanol in Brazil).

[START BOX 4.7 HERE]

Box 4.7: Bioethanol in Brazil: Innovation and Lessons for Technology Transfer

The use of sugarcane as a bioenergy source started in Brazil in the 1970s. Government and multinational car factories modified car engines nationwide so that vehicles running only on ethanol could be produced. As demand grew, production and distribution systems matured and costs came down (Soccol et al., 2010). After a transition period in which ethanol-only and gasoline-only cars were used, the flex-fuel era started in 2003, when all gasoline was blended with 25% ethanol (de Freitas and Kaneko, 2011). By 2010, around 80% of the car fleet in Brazil had been converted to use flex-fuel (Goldemberg, 2011; Su et al., 2015).

More than forty years of combining technology push and market pull measures led to the deployment of ethanol production, transportation and distribution systems across Brazil, leading to a significant decrease in CO_2 emissions (Macedo et al., 2008). Examples of innovations include: 1) the development of environmentally well-adapted varieties of sugarcane; 2) the development and scaling up of sugar fermentation in a non-sterile environment, and 3) the development of adaptations of car engines to use ethanol as a fuel isolated or in combination with gasoline (Amorim et al., 2011; de Freitas and Kaneko, 2011; de Souza et al., 2014). Public procurement, public investment in R&D and mandated fuel blends accompanying these innovations were also crucial (Hogarth, 2017). In the future, innovation could lead to viable partial carbon dioxide removal through deployment of BECCS associated with the bioethanol refineries (Fuss et al., 2014; Rochedo et al., 2016) (see Section 4.3.7).

Ethanol appears to reduce urban car emission of health-affecting ultrafine particles by 30% compared to gasoline-based cars, but increases ozone (Salvo et al., 2017). During the 1990s, when sugarcane burning was still prevalent, particulate pollution had negative consequences for human health and the environment (Ribeiro, 2008; Paraiso and Gouveia, 2015). While (Jaiswal et al., 2017) report bioethanol's limited impact on food production and forests in Brazil, despite the large scale, and attribute this to specific agro-ecological zoning legislation, various studies report adverse effects of bioenergy production through forest substitution by croplands (Searchinger et al., 2008), as well as impacts on biodiversity, water resources, and food security (Rathore et al., 2016). For new generation biofuels, feasibility and life cycle assessment studies can provide information on their impacts on environmental, economic, and social factors (Rathore et al., 2016).

Brazil and the European Union have tried to replicate Brazil's bioethanol experience in climatically suitable African countries. Although such technology transfer achieved relative success in Angola and Sudan, the attempts to set up bioethanol value chains did not pass the phase of political deliberations and feasibility studies elsewhere in Africa. Lessons learned include the need of political and economic stability of the donor country (Brazil) and the necessity of market creation to attract investments in first-generation biofuels alongside a safe legal and policy environment for improved technologies (Afionis et al., 2014; Favretto et al., 2017).

[END BOX 4.7 HERE]

Funding for R&D could come from various sources, including the general budget, energy or resource taxation, or emission trading schemes (see Section 4.4.5). Investing in climate-related R&D has as an additional benefit of building capabilities to implement climate mitigation and adaptation technologies (Ockwell et al., 2015). Countries regard innovation in general and climate technology specifically as a national interests issue, and addressing climate change primarily as in the global interest. Reframing part of climate policy as technology or industrial policy might therefore contribute to resolving the difficulties that continue to plague emission target negotiations (Faehn and Isaksen, 2016; Fischer et al., 2017; Lachapelle et al., 2017).

Climate technology transfer to emerging economies has happened regardless of international treaties, as these countries have been keen to acquire them, and companies have an incentive to access emerging markets to remain competitive (Glachant and Dechezleprêtre, 2016). However, the complexity of this transfer processes is high and they have to be conducted carefully by governments and institutions (Favretto et al., 2017). It is noticeable that the impact of the EU Emission Trading Scheme (EU ETS) on innovation is contested; recent work (based on lower carbon prices than anticipated for 1.5°C-consistent pathways) indicates that it is limited (Calel and Dechezleprêtre, 2016) but earlier assessments (Blanco et al., 2014) indicate otherwise.

4.4.4.4 Technology Transfer in the Paris Agreement

Technology development and transfer is recognised as an enabler of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2015) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). As previous sections have focussed on technology development and diffusion, this section focuses on technology transfer. Technology transfer can adapt technologies to local circumstances, reduce financing costs, develop indigenous technology, and build capabilities to operate, maintain, adapt and innovate on technology globally (Ockwell et al., 2015; de Coninck and Sagar, 2017). Technology cooperation could decrease global mitigation cost, and enhance developing countries' mitigation contributions (Huang et al., 2017a).

The international institutional landscape around technology development and transfer includes the UNFCCC (via its technology framework and technology mechanism including the Climate Technology Centre and Network (CTCN)), the United Nations (a technology facilitation mechanism for the SDGs) and a variety of non-UN multilateral and bilateral cooperation initiatives such as the Consultative Group on International Agricultural Research (CGIAR, founded in the 1970s), and numerous initiatives of companies, foundations, governments and non-governmental and academic organisations. Moreover, in 2015, twenty countries launched an initiative called 'Mission Innovation', seeking to double their energy R&D funding. At this point it is difficult to evaluate whether Mission Innovation achieved its objective (Sanchez and Sivaram, 2017). At the same time, the private sector started an initiative called the 'Breakthrough Energy Coalition'.

Most technology transfer is driven by through markets by the interests of technology seekers and technology holders, in particular in regions with well-developed institutional and technological capabilities such as developed and emerging nations (Glachant and Dechezleprêtre, 2016). However, the current international technology transfer landscape has gaps, in particular in reaching out to least-developed countries, where institutional and technology capabilities are limited (de Coninck and Puig, 2015; Ockwell and Byrne, 2016). On the one hand, literature suggests that the management or even monitoring of all these UN, bilateral, private and public initiatives may fail to lead to better results. On the other hand, it is probably more cost-effective to adopt a strategy of 'letting a thousand flowers bloom', by challenging and enticing researchers in the public and the private sector to direct innovation towards low-emission and adaptation options (Haselip et al., 2015). This can be done at the same time as mission-oriented research is adopted in parallel by the scientific community (Mazzucato, 2018).

At COP 21, the UNFCCC requested the Subsidiary Body for Scientific and Technological Advice (SBSTA) to initiate the elaboration of the technology framework established under the Paris Agreement (UNFCCC, 2015). Among other things, the technology framework would 'provide overarching guidance for the work of the Technology Mechanism in promoting and facilitating enhanced action on technology development and transfer in order to support the implementation of this Agreement' (this Agreement being the Paris Agreement). An enhanced guidance issued by the Technology Executive Committee (TEC) for preparing a Technology Action Plan (TAP) supports the new technology framework as well as Parties' long-term vision on technology development and transfer, reflected in the Paris Agreement (TEC, 2016).

4.4.5 Strengthening Policy Instruments and Enabling Climate Finance

Triggering rapid and far-reaching change in technical choices and institutional arrangements, consumption and lifestyles, infrastructure, land use and spatial patterns implies the ability to scale-up policy signals to enable the decoupling of GHGs emission, and economic growth and development (Section 4.2.2.3). Such a scale-up would also imply that potential short-term negative responses by populations and interest groups, that could block these changes from the outset, would need to be prevented or overcome. This section describes the size and nature of investment needs and the financial challenge over the coming two decades in the context of 1.5°C warmer worlds, assesses the potential and constraints of three categories of policy instruments that respond to the challenge, and explains the conditions for using them synergistically. The policy and finance instruments discussed in this section relate to Section 4.4.1 (on governance) and other Sections in 4.4.

4.4.5.1 The Core Challenge: Cost Efficiency, Coordination of Expectations and Distributive Effects

Box 4.8 shows that the average estimates by seven models of annual investments needs in the energy system is around 2.38 trillion USD_{2010} (1,38 to 3,25) between 2016 and 2035. This represents between 2.53% (1.6% to 4%) of the world GDP in Market Exchange Rates (MER) and 1.7% of the world GDP in purchasing power parity (PPP). OECD investment assessments for a 2°C-consistent transition suggest that including investments in transportation and in other infrastructure would increase the investment needs by a factor of three. Other studies not included in Box 4.8, in particular by the World Economic Forum (World Economic Forum, 2013) and the Global Commission on the Economy and Climate (GCEC, 2014) confirm these orders of magnitude of investment.

[START BOX 4.8 HERE]

Box 4.8: Investment Needs and the Financial Challenge of Limiting Warming to 1.5°C

The peer-reviewed literature that estimates the investment needs to scale up the response to limit warming to 1.5°C is limited (see Section 4.6). This box attempts to bring together available estimates of the order of magnitude of these investments to provide the context for global and national financial mobilisation policy and related institutional arrangements.

Table 1 in this box presents mean annual investments up to 2035, based on three studies (after clarifying their scope and harmonising their metrics): an ensemble of six integrated assessment models (See Chapter 2); an OECD (Organisation for Economic Co-operation and Development) scenario for a 2°C limit (OECD, 2017a) and scenarios from the International Energy Agency (IEA) (IEA, 2016c). All three sources provide estimates for the energy sector for various for mitigation scenarios. The OECD estimate also covers transportation and other infrastructure (water, sanitation, and telecommunication), which are essential to deliver the Sustainable Development Goals (SDGs), including SDG7 on clean energy access, and enhance the adaptive capacity to climate change.

Box 4.8, Table 1: Estimated annualised mitigation investment needed to stay well below 2°C (2015–2035 in trillion USD at market exchange rates)

	Energy investments	Of which demand side	Transport	Other infra-structures	Total	Ratio to MER GDP
IAM Baseline (mean)	1.96	0.24			1.96	1.8%
IAM NDC (mean)	2.04	0.28			2.04	1.9%
IAM 2°C (mean)	2.19	0.38			2.19	2.1%
IAM 1.5°C (mean)	2.32	0.45			2.32	2.2%
IEA NDC	*2.40*	*0.72*	*0.35*		*2.40*	2.3%
IEA 1.5°C	*2.76*	*1.13*	*0.55*		*2.76*	2.7%
Mean IAM-IEA, 1.5°C	**2.38**	**0.54**			**2.38**	**2.53%**
Min IAM-IEA, 1.5°C	1.38	0.38			1.38	1.6%
Max IAM-IEA, 1.5°C	3.25	1.13			3.25	4.0%
OECD Baseline	*1.91*	*0.36*	*2.46*	*1.37*	*5.74*	5.4%
OECD 2°C	*2.13*	*0.40*	*2.73*	*1.52*	*6.38*	6.0%

The mean incremental share of annual mitigation investments to stay well below 2°C is 0.36% (between 0.2–1%) of global Gross Domestic Product (GDP) over 2015–2035. Since Gross Fixed Capital Formation (GFCF) is about 24% of global GDP, the estimated incremental energy investments between a baseline and a 1.5°C transition would be approximately 1.5% (between 0.8–4.2%) of projected total world investments. Given the uncertainty in these estimates, decision-makers could lower the probability of the most pessimistic assumptions by implementing policies to accelerate technical change (Section 4.4.5).

While total incremental investment for a 2°C-consistent pathway, including for transportation and other infrastructure, is estimated at 2.5% of global GFCF, there is no comprehensive study or estimate of these investments for a 1.5°C limit. For a 1.5°C-consistent pathway, the anticipated incremental 'other investments' might be lower thanks to lower investment needs in adaptation.

The issue, from a macroeconomic perspective, is whether these investments would be funded by higher savings at the costs of lower consumption. This would mean a 0.5% reduction in consumption for the energy sector for 1.5°C. Note that for a 2°C scenario, this reduction would be 0.8% if we account for the investment needs of all infrastructure sectors . Assuming a constant saving ratio, this can be enabled by reallocating existing capital flows towards infrastructure. In addition to these incremental investments, the amount of redirected investments is relevant from a financial perspective. In the reported Integrated Assessment Model (IAM) energy sector scenarios, about three times the incremental investments is redirected. There is no such assessment for the other sectors. The OECD report suggests that these ratios might be higher.

These orders of magnitude of investment can be compared to the available statistics of the global stock of 386 trillion USD of financial capital, which consists of 100 trillion USD in bonds (SIFMA, 2017), around 60 trillion USD in equity (The World Bank Data, 2018), and 226 trillion USD of loans managed by the banking system (IIF, 2017)(World Bank, 2018a). The long term rate of return (interest plus increase of shareholder value) is about 3% on bonds, 5% on bank lending, 7% on equity, leading to a weighted mean cost of capital of 3.4% in real terms (5.4% in nominal terms). Using 3.4% as a lower bound and 5% as a higher bound (following (Piketty, 2014)) and taking a conservative assumption that global financial capital grows at the same rate as global GDP, the estimated financial capital revenues would be between 16.8 and 25.4 trillion USD.

Assuming that a quarter of these investments comes from public funds (as estimated by the World Bank (World Bank, 2018a)), the amount of private resources needed to enable an energy sector transition is between 3.3% and 5.3% of annual capital income and between 5.6% and 8.3% of these revenues for all infrastructure to meet the 2°C target and the SDGs.

Since the financial system has limited fungibility across budget lines, changing the partitioning of investments is not a zero-sum game. An effective policy regime could encourage investment managers to change their asset allocation. Part of the challenge may lie in increasing the pace of financing of low-emission assets to compensate for a possible 38% decrease, by 2035, in the value of fossil fuel assets (energy sector and indirect holdings in downstream uses like automobiles) (Mercure et al., 2018).

[END BOX 4.8 HERE]

The average increase of investment in the energy sector resulting from Box 4.8 represents a mean value of 1.5% of the global Gross Fixed Capital Formation (GFCF) compared with the baselines scenario in Market Exchange Rate (MER) and a little over 1% in Purchasing Power Parity (PPP). Including infrastructure investments would raise this to 2.5% and 1.7% respectively[9].

These incremental investments could be funded through a drain on consumption (Bowen et al., 2017) which would necessitate between 0.68% and 0.45% lower global consumption than in the baseline. But, consumption at constant savings/consumption ratio can alternatively be funded by shifting savings towards productive adaptation and mitigation investments, instead of real-estate sector and liquid financial products. This response depends upon whether it is possible to close the global investment funding gap for infrastructure that potentially inhibits growth, through structural changes in the global economy. In this case, investing more in infrastructures would not be an incremental cost in terms of development and welfare (IMF, 2014; Gurara et al., 2017)

Investments in other (non-energy system) infrastructure to meet development and poverty reduction goals can strengthen the adaptive capacity to address climate change, and is difficult to separate from overall sustainable development and poverty alleviation investments (Hallegatte and Rozenberg, 2017). The magnitude of potential climate change damages is related to pre-existing fragility of impacted societies (Hallegatte et al., 2007). Enhancing infrastructure and service provision would lower this fragility, for example through the provision of universal (water, sanitation, telecommunication) service access (Arezki et al., 2016).

The main challenge is thus not just a lack of mobilisation of aggregate resources but of redirection of savings towards infrastructure, and the further redirection of these infrastructure investments towards low-emission options. If emission-free assets emerge fast enough to compensate for the devaluation of high-emission assets, the sum of the required incremental and redirected investments in the energy sector would (up to 2035) be equivalent to between 3.3% and 5.3% of the average annual revenues of the private capital stock (see Box 4.8) and to 5.6% and 8.3%, including all infrastructure investments.

The interplay between mechanisms of financial intermediation and the private risk-return calculus is a major barrier to realising these investments (Sirkis et al., 2015). This obstacle is not specific to climate mitigation investments but also affects infrastructure and has been characterised as the gap between the ‘propensity to save’ and the ‘propensity to invest’ (Summers, 2016). The issue is whether new financial instruments could close this gap and inject liquidity into the low-emission transition, thereby unlocking new economic opportunities (GCEC, 2014; NCE, 2016). By offsetting the crowding-out of other private and public investments (Pollitt and Mercure, 2017) the ensuing ripple effect could reinforce growth and the sustainability of development (King, 2011; Teulings and Baldwin, 2014) and potentially triggering a new growth cycle (Stern, 2013, 2015). In this case, a massive mobilisation of low-emission investments would

[9] FOOTNOTE: A calculation in MER tends indeed to underestimate the world GDP and its growth by giving a lower weight to fast growing developing countries whereas a calculation in PPP tends to overestimate it. The difference between the value of two currencies in PPP and MER should vanish as the gap of the income levels of the two concerned countries decreases. Accounting for this trend in modelling is challenging.

require a significant effort, but may be complementary to sustainable development investments.

This uncertain but potentially positive outcome might be constrained by the higher energy costs of low-emission options in the energy and transportation sectors. The price envelope of worldwide marginal abatement costs for 1.5°C-consistent pathways reported in Chapter 2 is 135–475 USD tCO_2^{-1} in 2030 and 245–1100 USD tCO_2^{-1} in 2050, which is between two or three times higher than for a 2°C limit.

These figures are consistent with the dramatic reduction in the unit costs of some low-emission technical options (for example solar PV, LED lighting) over the past decade (OECD, 2017c) (see Section 4.3.1). Yet, there are multiple constraints to a system-wide energy transition. Lower costs of some supply and demand-side options does not always result in a proportional decrease in energy system costs. The adoption of alternative options can be slowed down by increasing costs of decommissioning existing infrastructure, inertia of market structures, cultural habits and by risk-adverse user behaviour (see Sections 4.4.1 to 4.4.3). Learning-by-doing processes and R&D can accelerate the cost-efficiency of low-emission technology but often imply higher early-phase costs. The German energy transition resulted in high consumer prices for electricity in Germany (Kreuz and Müsgens, 2017) and needed strong accompanying measures to succeed.

One key issue is that energy costs can propagate across sectors amplifying overall production costs. During the early stage of a low-emission transition, an increase in the prices of non-energy goods could cause lower consumer purchasing power and final demand. A rise of energy prices has a proportionally greater impact in developing countries that are in a catch-up phase, with strong dependence on energy-intensive sectors (Crassous et al., 2006; Luderer et al., 2012) and a higher ratio of energy to labour cost (Waisman et al., 2012). This explains why with lower carbon prices, similar emission reductions are reached in South Africa (Altieri et al., 2016) and Brazil (La Rovere et al., 2017a) compared to developed countries. However, three distributional issues emerge.

First, in the absence of countervailing policies, higher energy costs have an adverse effect on the distribution of welfare (see also Chapter 5). The negative impact is inversely correlated with the level of income (Harberger, 1984; Fleurbaey and Hammond, 2004) and positively correlated with the share of energy in the households budget, which is high for low- and middle- income households (Proost and Van Regemorter, 1995; Barker and Kohler, 1998; West and Williams, 2004; Chiroleu-Assouline and Fodha, 2011). Moreover, climatic conditions and the geographical conditions of human settlements matter for heating and mobility needs (see Chapter 5). Medium-income populations in the suburbs, remote and low-density regions can be as vulnerable as residents of low-income urban areas. Poor households with low levels of energy consumption are also impacted by price increases of non-energy goods caused by the propagation of energy costs (Combet et al., 2010; Dubois, 2012). These impacts are generally not offset by non-market co-benefits of climate policies for the poor (Baumgärtner et al., 2017).

A second matter of concern is the distortion of international competition and employment implications in case of uneven carbon constraints, especially for energy-intensive industries (Demailly and Quirion, 2008). Some of these industries are not highly exposed to international competition because of their very high transportation costs per unit value added (Sartor, 2013; Branger et al., 2016), but other industries could suffer severe shocks, generate 'carbon leakage' through cheaper imports from countries with lower carbon constraints (Branger and Quirion, 2014) and weaken the surrounding regional industrial fabric with economy-wide and employment implications.

A third challenge is the depreciation of assets whose value is based on the valuation of fossil energy resources of which future revenues may decline precipitously with higher carbon prices (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015) and on emission-intensive capital stocks (Guivarch and Hallegatte, 2011; OECD/IEA/NEA/ITF, 2015; Pfeiffer et al., 2016). This raises issues of changes in industrial structure, adaptation of worker skills and of stability of financial, insurance and social security systems. These systems are in part based on current holdings of carbon-based assets whose value might decrease by 38% by the mid-2030s (Mercure et al., 2018). This stranded asset challenge may be exacerbated by a decline of export revenues of fossil fuel producing countries and regions (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015).

These distributional issues, if addressed carefully and expeditiously, could affect popular sensitivity towards climate policies. Addressing them could mitigate adverse macroeconomic effects on economic growth and employment that could undermine the potential benefits of a redirection of savings and investments towards 1.5°C-consistent pathways.

Strengthening policy instruments for a low-emission transition would thus need to reconcile three objectives: i) handling the short-term frictions inherent to this transition in an equitable way, ii) minimising these frictions by lowering the cost of avoided GHGs emissions, and iii) coordinating expectations of multiple stakeholders at various decision-making levels to accelerate the decline in costs of emission reduction, efficiency and decoupling options and maximising their co-benefits (see the practical example of lowering car use in cities in Box 4.9).

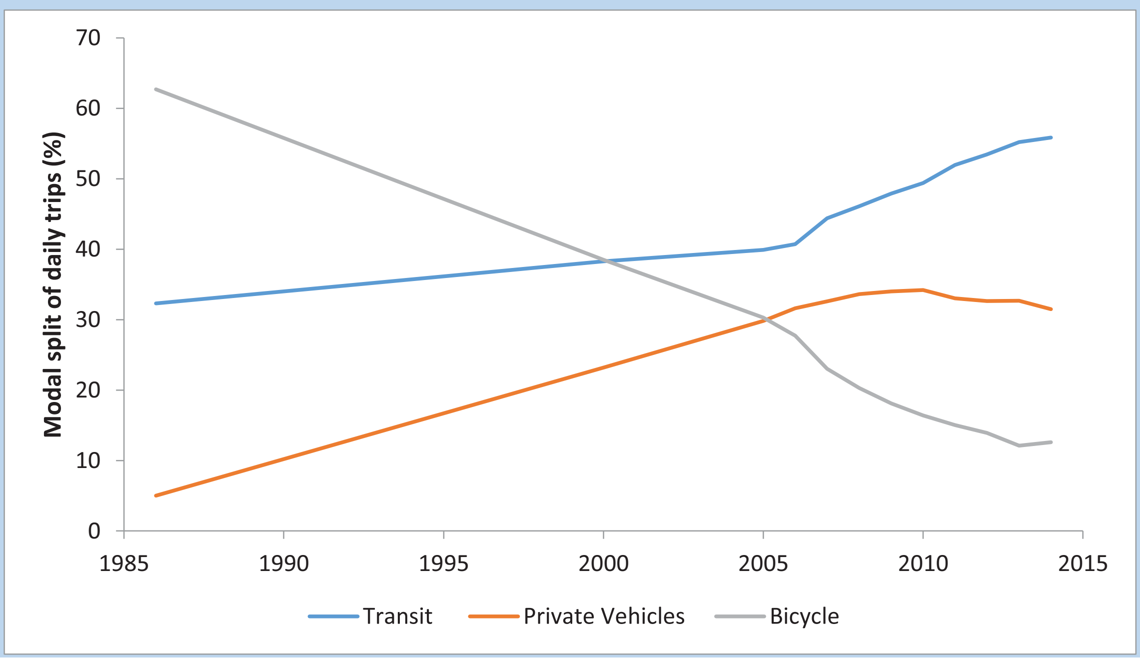
Three categories of policy tools would be available to meet the distributional challenges: carbon pricing, regulatory instruments and information and financial tools,. Each of them has its own strength and weaknesses, and in a 1.5°C perspective, policy tools would have to be both upscale and better coordinated in packages in a synergistic manner.

[START BOX 4.9 HERE]

Box 4.9: Emerging cities and 'peak car use': Evidence of decoupling in Beijing

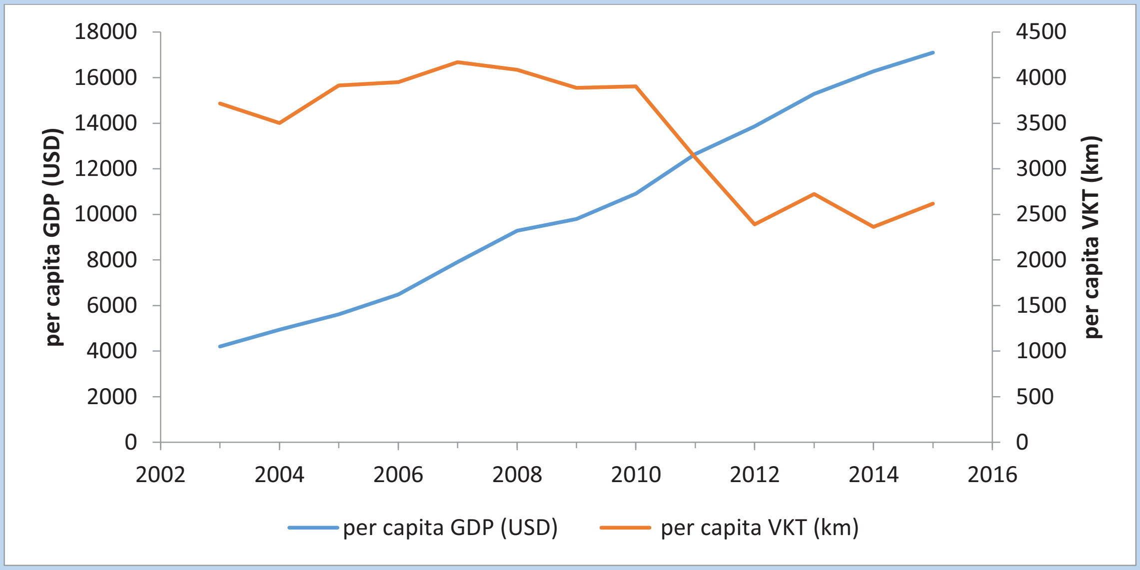
The phenomenon of 'peak car use', or reductions in per capita car use, provides hope for continuing reductions in greenhouse gas from oil consumption (Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011; Goodwin and Van Dender, 2013). The phenomenon has been mostly associated with developed cities apart from some early signs in Eastern Europe, Latin America and China (Newman and Kenworthy, 2015). New research indicates that peak car is now also underway in China (Gao and Newman, 2018).

China's rapid urban motorisation has resulted from strong economic growth, fast urban development and the prosperity of the Chinese automobile industry (Gao and Kenworthy, 2015). However, recent data (Gao and Newman, 2018) suggest the first signs of a break in the growth of car use expressed in percentage of daily trips as the growth in mass transit, primarily caused by the expansion of Metro systems, is becoming more significant (see Box 4.9, Figure 1).



Box 4.9, Figure 1: The modal split data in Beijing between 1986 and 2014. Source: (Gao and Newman, 2018).

Chinese urban fabrics, featuring traditional dense linear forms and mixed land use, favour mass transit systems over automobiles (Gao and Newman, 2018). The data show that the decline in car use did not impede economic development but Vehicle Kilometres of Travel (VKT) growth has decoupled absolutely from GDP as shown in Box 4.9, Figure 2 below.



Box 4.9, Figure 2: Peak car in Beijing: relationships between economic performance and private automobile use in Beijing from 1986 to 2014. VKT is Vehicle Kilometres of Travel. Source: (Gao and Newman, 2018).

[END BOX 4.9 HERE]

4.4.5.2 Carbon Pricing: Necessity and Constraints

For long, economic literature has argued that climate and energy policy only grounded in regulation, standards and public funding of R&D is at risk of being influenced by political and administrative arbitrariness, which could raise the costs of implementation. This literature has argued that it may be more efficient to make these costs explicit through carbon taxes and carbon trading, securing the abatement of emissions in places and sectors where it is cheapest (IPCC, 1995, 2001; Gupta et al., 2007; Somanathan et al., 2014).

In a frictionless world, a unique world carbon price could minimise the social costs of the low carbon transition by equating the marginal costs of abatement across all sources of emissions. This implies that investors will be able to make the right choices under perfect foresight and that domestic and international compensatory transfers offset the adverse distributional impacts of higher energy prices and their consequences on economic activity. In the absence of transfers targeted in function of countries market structures (Boeters, 2014), carbon prices are no longer optimal (Böhringer et al. 2009; Böhringer and Alexeeva-Talebi 2013) and need to be differentiated by jurisdiction (Chichilnisky and Heal, 2000; Sheeran, 2006) in function of the countries' social welfare function. This differentiation could in turn raise concerns of distortions in international competition (Hourcade et al., 2001; Stavins et al., 2014).

Obstacles to enforcing a unique world carbon price in the short-run would not necessarily crowd out explicit national carbon pricing, for three reasons. First, it could restrain an emissions rebound due to a higher consumption of energy services enabled by efficiency gains, if energy prices do not change (Greening et al., 2000; Fleurbaey and Hammond, 2004; Sorrell et al., 2009; Guivarch and Hallegatte, 2011; Chitnis and Sorrell, 2015; Freire-González, 2017). Second, it could hedge against the arbitrariness of regulatory policies. Third, 'revenue neutral' recycling, at a constant share of taxes on GDP, into lowering some existing taxes compensates at least part of the propagation effect of higher energy costs (Stiglitz et al., 2017). The substitution by carbon taxes of taxes that cause distortions on the economy can counteract the regressive effect of higher energy prices. For example, offsetting increased carbon prices with lower labour taxes can potentially decrease labour costs (without affecting salaries), enhance employment and reduce the attractiveness of informal economic activity (Goulder, 2013).

The conditions under which an economic gain along with climate benefit (a 'double dividend') can be expected are well documented (Goulder, 1995; Bovenberg, 1999; Mooij, 2000)
. In the context of OECD countries, the literature examines how carbon taxation could substitute for other taxes to fund the social security system (Combet, 2013). The same general principles apply for countries that are building their social welfare system such as China (Li and Wang, 2012) or Brazil (La Rovere et al., 2017a) but an optimal recycling scheme could differ based on the structure of the economy (Lefèvre et al. 2018).

In every country the design of carbon pricing policy implies a balance between incentivising low-carbon behaviour and mitigating the adverse distributional consequences of higher energy prices (Combet et al., 2010). Carbon taxes can offset these effects if their revenues are redistributed through rebates to poor households. Other options include the reduction of value added taxes for basic products or direct benefit transfers to enable poverty reduction (see (Winkler et al., 2017) for South Africa and (Grottera et al., 2016) for Brazil). This is possible because higher income households pay more in absolute terms, even though their carbon tax burden is a relatively smaller share of their income (Arze del Granado et al., 2012).

Ultimately, the pace of increase of carbon prices would depend on the pace at which they can be embedded in a consistent set of fiscal and social policies. This is why, after a quarter century of academic debate and experimentation (see IPCC WGIII reports since the SAR), a gap persists with respect to 'switching carbon prices' needed to trigger rapid changes. In 2016, only 15% of global emissions are covered by carbon pricing, three-quarters of which with prices below 10 USD tCO_2^{-1} (World Bank, 2016). This is too low to outweigh the 'noise' from the volatility of oil markets (in the range of 100 USD tCO_2^{-1} over the past decade), of other price dynamics (interest rates, currency exchange rates and real estate prices) and of regulatory policies in energy, transportation and industry. For example, the dynamics of mobility depend upon a trade-off between housing prices and transportation costs in which the price of real estate and the inert endowments in public transport play as important a role as liquid fuel prices (Lampin et al., 2013).

These considerations apply to attempts to secure a minimum price in carbon trading systems (Wood and Jotzo, 2011; Fell et al., 2012; Fuss et al., 2018) and to the reduction of fossil fuel subsidies. Estimated at 650 billion USD in 2015 (Coady et al., 2017), they represent 25–30% of government revenues in forty (mostly developing) countries (IEA, 2014b). Reducing these subsidies would contribute to reaching 1.5°C-consistent pathways, but raises similar issues as carbon pricing around long-term benefits and short-term costs (Jakob et al., 2015; Zeng and Chen, 2016), as well as social impacts.

Explicit carbon prices are thus a necessary 'lubricant' to accommodate the general equilibrium effects of higher energy prices but may not suffice to trigger the low-carbon transition because of a persistent 'implementation gap' between the aspirational carbon prices and those that can practically be enforced. When systemic changes, such as those needed for 1.5°C-consistent pathways, are at play on many dimensions of development, price levels 'depend on the path and the path depends on political decisions' (Dréze and Stern, 1990).

4.4.5.3 Regulatory measures and information flows

Regulatory instruments are a common tool for improving energy efficiency and enhancing renewable energy in OECD countries (e.g., US, Japan, Korea, Australia, the EU) and, more recently, in developing countries (M.H. Scott et al., 2015; Brown et al., 2017) including constraints on the import of products banned in other countries (Knoop and Lechtenböhmer, 2017).

For energy efficiency, these instruments include end-use standards and labelling for domestic appliances, lighting, electric motors, water heaters and air-conditioners. They are often complemented by mandatory efficiency labels to attract consumers' attention and stimulate the manufacture of more efficient products (Girod et al., 2017). Experience shows that these policy instruments are effective only if they are regularly reviewed to follow technological developments, as in the 'Top Runner' programme for domestic appliances in Japan (Sunikka-Blank and Iwafune, 2011).

In four countries, efficiency standards (e.g. miles/gallon or level of CO_2 emission per km) have been used in the transport sector, for light and heavy-duty vehicles, which have spill-overs for the global car industry. In the EU (Ajanovic and Haas, 2017) and the US (Sen et al., 2017) vehicle manufacturers need to meet an annual CO_2 emission target for their entire new vehicle fleet. This allows them to compensate through the introduction of low-emission vehicles for the high-emission ones in the fleet. This leads to increasingly efficient fleets of vehicles over time, but does not necessarily limit the driven distance.

Building codes that prescribe efficiency requirements for new and existing buildings have been adopted in many OECD countries (Evans et al., 2017) and are regularly revised to increase their efficiency per unit of floor space. Building codes can avoid the lock-in of rapidly urbanising countries to poorly performing buildings that remain in use for the next 50–100 years (Ürge-Vorsatz et al., 2014). In OECD countries, however, their main role is to incentivise the retrofit of existing buildings. In addition of the convergence of these codes to Net Zero Energy Buildings (D′Agostino, 2015), a new focus should be placed, in the context of 1.5°C-consistent pathways, on public and private co-ordination to achieve better integration of building policies with the promotion of low-emission transportation modes (Bertoldi, 2017).

The efficacy of regulatory instruments can be reinforced by economic incentives, such as feed-in tariffs based on the quantity of renewable energy produced, subsidies or tax exemptions for energy savings (Bertoldi et al., 2013; Ritzenhofen and Spinler, 2016; García-Álvarez et al., 2017; Pablo-Romero et al., 2017), fee-bates, and 'bonus-malus' that foster the penetration of low-emission options (Butler and Neuhoff, 2008). Economic incentives can also be combined with direct use market-based instruments, for example combining, in the United States and, in some EU countries, carbon trading schemes with Energy Savings Obligations for energy retailers (Haoqi et al., 2017), or with Green Certificates for renewable energy portfolio standards (Upton and Snyder, 2017). Scholars have investigated caps on utilities' energy sales (Thomas et al., 2017) and emission caps at a personal level (Fawcett et al., 2010).

In combination with the funding of public research institutes, grants or subsidies also support R&D, where risk and the uncertainty about long-term perspectives can reduce the private sector's willingness to invest in low-emission innovation (see also Section 4.4.4). Subsidies can take the form of rebates on Value-Added Tax (VAT), of direct support to investments (e.g. renewable energy or refurbishment of buildings) or feed-in tariffs (Mir-Artigues and del Río, 2014). They can be provided by the public budget, via consumption levies, or via the revenues of carbon taxes or pricing. Fee-bates, introduced in some countries (for example for cars), have had a neutral impact on public budgets by incentivising low-emission products and penalising high-emission ones (de Haan et al., 2009).

All policy instruments can benefit from information campaigns (e.g., TV ads) tailored to specific end-users. A vast majority of public campaigns on energy and climate have been delivered through mass-media channels, and advertising-based approaches (Corner and Randall, 2011; Doyle, 2011). Although some authors report large savings obtained by such campaigns, most agree that the effects are short-lived and decrease over time (Bertoldi et al., 2016). Recently, focus has been placed on the use of social norms to motivate behavioural changes (Allcott, 2011; Alló and Loureiro, 2014). More on strategies to change behaviour can be found in section 4.4.3.

4.4.5.4 Scaling-up Climate Finance and De-Risking Low-Emission Investments

The redirection of savings towards low-emission investments may be constrained by enforceable carbon prices, implementation of technical standards and the short-term bias financial systems (Miles, 1993;

Bushee, 2001; Black and Fraser, 2002). The many causes of this bias are extensively analysed in economic literature (Tehranian and Waegelein, 1985; Shleifer and Vishny, 1990; Bikhchandani and Sharma, 2000) including their link with prevailing patterns of economic globalisation (Krugman, 2009; Rajan, 2011) and the chronic under-investment in long-term infrastructure (IMF, 2014). Emerging literature explores how to overcome this through reforms targeted to bridge the gap between short-term cash balances and long-term low-emission assets and to reduce the risk-weighted capital costs of climate-resilient investments. This gap was qualified by the Governor of the Bank of England as a Tragedy of the Horizons (Carney, 2016) that constitutes a threat to the stability of the financial system, is confirmed by the literature (Arezki et al., 2016; Christophers, 2017). This potential threat would encompass the impact of climate events on the value of assets (Battiston et al., 2017), liability risks (Heede, 2014) and the transition risk due to devaluation of certain classes of assets (Platinga and Scholtens, 2016).

The financial community's attention to climate change grew after COP 15 (ESRB ASC, 2016). This led to the introduction of climate-related risk disclosure in financial portfolios (UNEP, 2015) placing it on the agenda of G20 Green Finance Study Group and of the Financial Stability Board. This led to the creation of low-carbon financial indices that investors could consider as a 'free option on carbon' to hedge against risks of stranded carbon intensive assets (Andersson et al., 2016). This could also accelerate the emergence of climate-friendly financial products such as green or climate bonds, The estimated value of the Green bonds market in 2017 is USD 200 billion (BNEF, 2017). The bulk of these investments are in renewable energy, energy efficiency and low-emission transport (Lazurko and Venema, 2017), with only 4% for adaptation (OECD, 2017b). One major issue is whether individual strategies based on improved climate-related information alone will enable the financial system to allocate capital in an optimal way (Christophers, 2017) since climate change is a systemic risk (Schoenmaker and van Tilburg, 2016) (CISL, 2015).

The readiness of financial actors to reduce investments in fossil fuels is a real trend (Platinga and Scholtens, 2016; Ayling and Gunningham, 2017) but they may not resist the attractiveness of carbon-intensive investments in many regions. Hence, decarbonising an investment portfolio is not synonymous with investing massively in low-emission infrastructure. Scaling up climate-friendly financial products may depend upon a business context conducive to the reduction of the risk-weighted capital costs of low-emission projects. The typical leverage of public funding mechanisms for low-emission investment is low (2 to 4) compared with (10 to 15) in other sectors (Maclean et al., 2008; Ward et al., 2009; MDB, 2016). This is due to the interplay of the uncertainty of emerging low-emission technologies in the midst of their learning-by-doing cycle, and of uncertain future revenues due to volatility of fossil fuel prices (Roques et al., 2008; Gross et al., 2010) and of uncertainty around regulatory policies. This inhibits low-emission investments by corporations functioning under a 'shareholder value business regime' (Berle and Means, 1932; Froud et al., 2000; Roe, 2001) and actors with restricted access to capital (e.g. cities, local authorities, SMEs and households).

De-risking policy instruments to enable low-emission investment encompass interest rate subsidies, fee-bates, tax breaks, concessional loans from development banks, and public investment funds, including revolving funds. Given the constraints on public budgets, public guarantees can be used to secure high leverage of public financing. They imply a full direct burden on public budgets only in case of default of the project. They could back for example various forms of Green Infrastructure Funds (De Gouvello and Zelenko, 2010; Emin et al., 2014; Studart and Gallagher, 2015)[10].

The risk of defaulting can be mitigated by strong Measurement, Reporting and Verifying (MRV) systems (Bellassen et al., 2015)and by the use of notional prices recommended in public economics and currently in use in France and the UK, to calibrate public support to the provision of public goods in case of persisting distortions in pricing (Stiglitz et al., 2017). Some suggest linking these notional prices to 'social, economic and environmental value of voluntary mitigation actions' recognised by the COP21 Decision accompanying the Paris Agreement (paragraph 108) (Hourcade et al., 2015; La Rovere et al., 2017b; Shukla et al., 2017), in order to incorporate the co-benefits of mitigation.

[10] FOOTNOTE: One prototype is the World Bank's Pilot Auction Facility on Methane and Climate Change

Such public guarantees ultimately amount to money issuance backed by low-emission projects as collateral. This explains the potentially strong link between global climate finance and the evolution of the financial and monetary system. Amongst suggested mechanisms for this evolution are the use of International Monetary Fund's (IMF's) Special Drawing Rights to fund the paid-in capital of the Green Climate Fund (Bredenkamp and Pattillo, 2010) and the creation of carbon remediation assets at a predetermined face value per avoided tonne of emissions (Aglietta et al., 2015a, b). Such a predetermined value could hedge against the fragmentation of climate finance initiatives and support the emergence of financial products backed by a new class of long-term assets.

Combining public guarantees at a predetermined value of avoided emissions, in addition to improving the consistency of non-price measures, could support the emergence of financial products backed by a new class of certified assets to attract savers in search of safe and ethical investments (Aglietta et al., 2015b). It could hedge against the fragmentation of climate finance initiatives and provide a mechanism to compensate for the 'stranded' assets caused by divestment in carbon-based activities and in lowering the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). These new assets could also facilitate a low-carbon transition for fossil-fuel producers and help them to overcome the 'resource curse' (Ross, 2015; Venables, 2016).

Blended injection of liquidity has monetary implications. Some argue that this questions the premise that money should remain neutral (Annicchiarico and Di Dio, 2015, 2016; Nikiforos and Zezza, 2017). Central Banks or financial regulators could act as a facilitator of last resort for low-emission financing instruments, that could in turn lower the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). This may, in time, lead to the use of carbon-based monetary instruments to diversify reserve currencies (Jaeger et al., 2013) and differentiate reserve requirements (Rozenberg et al., 2013) in the perspective of a Climate Friendly Bretton Woods (Sirkis et al., 2015; Stua, 2017).

4.4.5.5 Financial Challenge for Basic Needs and Adaptation Finance

Adaptation finance is difficult to quantify for two reasons. The first is that it is very difficult to isolate specific investment needs to enhance climate resilience from the provision of basic infrastructure that are currently underinvested (IMF, 2014; Gurara et al., 2017). The UNEP (2016) estimate of investment needs on adaptation in developing countries between 140–300 billion USD yr^{-1} in 2030, a major part being investment expenditures that are complementary with SDG-related investments focussed on universal access to infrastructure and services and meeting basic needs. Many climate adaptation-centric financial incentives are relevant to non-market services, offering fewer opportunities for market revenues while they contribute to creating resilience to climate impacts.

Hence, adaptation investments and the provision of basic needs would typically have to be supported by national and sub-national government budgets together with support from overseas development assistance and multilateral development banks (Fankhauser and Schmidt-Traub, 2011; Adenle et al., 2017; Robinson and Dornan, 2017), and a slow increase of dedicated NGO and private climate funds (Nakhooda and Watson, 2016). Even though the UNEP estimates of the costs of adaptation might be lower in a 1.5°C world (Climate Analytics, 2015) they would be higher than the UNEP 22.5 USD billion estimates of the bilateral and multilateral funding for climate change adaptation in 2014. Currently, 18–25% of climate finance flows to adaptation in developing countries (OECD, 2015, 2016a; Shine and Campillo, 2016). It remains fragmented, with small proportions flowing through UNFCCC channels (AdaptationWatch, 2015; Roberts and Weikmans, 2017).

Means of raising resources for adaptation, achieving the SDG and meeting basic needs (Durand et al., 2016; Roberts et al., 2017) include the reduction of fossil fuel subsidies (Jakob et al., 2016), increasing revenues from carbon taxes (Jakob et al., 2016), levies on international aviation and maritime transport and share of the proceeds of financial arrangements supporting mitigation activities (Keen et al., 2013). Each have different redistribution implications. Challenges, however, include the efficient use of resources, the emergence of long-term assets using infrastructure as collateral and the capacity to implement small-scale adaptation and the mainstreaming of adaptation in overall development policies. There is thus a need for greater policy coordination (Fankhauser and McDermott, 2014; Morita and Matsumoto, 2015; Sovacool et al., 2015, 2017; Lemos et al., 2016; Adenle et al., 2017; Peake and Ekins, 2017) that includes robust mechanisms for tracking, reporting, and ensuring transparency of adaptation finance (Donner et al., 2016; Pauw et al., 2016a; Roberts and Weikmans, 2017; Trabacchi and Buchner, 2017) and its consistency with the provision of basic needs (Hallegatte et al., 2016).

4.4.5.6 Towards Integrated Policy Packages and Innovative Forms of Financial Cooperation

Carbon prices, regulation and standards, improved information and appropriate financial instruments can work synergistically to meet the challenge of 'making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development', as in Article 2 in the Paris Agreement.

There is growing attention to combine the use of policy instruments that actually address three domains of action: the behavioural changes, the economic optimisation and the long-term strategies (Grubb et al., 2014). For example, de-risking low-emission investments would result in higher volumes of low-emission investments, and would in turn lead to a lower switching price for the same climate ambition (Hirth and Steckel, 2016). In the reverse direction, higher explicit carbon prices may generate more low-emission projects for a given quantum of de-risking. For example, efficiency standards for housing can increase the efficacy of carbon prices and overcome the barriers coming from the high discount rates used by households (Parry et al., 2014), while explicit and notional carbon prices can lower the risk of arbitrary standards. The calibration of innovative financial instruments to notional carbon prices could encourage large multinational companies to increase their level of internal carbon prices (UNEP, 2016). These notional prices could be higher than explicit carbon prices because they redirect new hardware investments without an immediate impact on existing capital stocks and associated interests.

Literature however shows that conflicts between poorly articulated policy instruments can undermine their efficiency (Lecuyer and Quirion, 2013; Bhattacharya et al., 2017; García-Álvarez et al., 2017). As has been illustrated in Europe, commitment uncertainty and lack of credibility of regulation have consistently led to low carbon prices in the case of the EU Emission Trading System (ETS; Koch et al., 2014; 2016). A comparative study shows how these conflicts can be avoided by policy packages that integrate many dimensions of public policies and are designed to match institutional and social context of each country and region (Bataille et al., 2015).

Even though policy packages depend upon domestic political processes, they might not reinforce the NDCs at a level consistent with the 1.5°C transition without a conducive international setting where international development finance plays a critical role. Section 4.4.1 explores the means of mainstreaming climate finance in the current evolution of the lending practices of national and multilateral bank (Badré, 2018). This could facilitate the access of developing countries to loans via bond markets at low interest rates, encouragement of the emergence of new business models for infrastructure, and encouragement of financial markets to support small-scale investments (Déau and Touati, 2017).

These financial innovations may involve non-state public actors like cities and regional public authorities that govern infrastructure investment, enable energy and food systems transitions and manage urban dynamics (Cartwright, 2015). They would help for example in raising USD 4.5–5.4 trillion yr^{-1} from 2015 to 2030 announced by the Cities Climate Finance Leadership Alliance (CCFLA, 2016) to achieve the commitments by the Covenant of Mayors of many cities to long-term climate targets (Kona et al., 2018).

The evolution of global climate financial cooperation may involve Central Banks, financial regulatory authorities, multilateral and commercial banks. There are still knowledge gaps about the form, structure and potential of these arrangements. They could be viewed as a form of a burden-sharing between high, medium and low-income countries to enhance, the deployment of ambitious Nationally

Determined Contributions (NDCs), and new forms of Common But Differentiated Responsibility and Respective Capabilities (Edenhofer et al., 2015; Hourcade et al., 2015; Ji and Sha, 2015).

4.5 Integration and Enabling Transformation

4.5.1 Assessing Feasibility of Options for Accelerated Transitions

Chapter 2 shows that 1.5°C-consistent pathways involve rapid, global climate responses to reach net-zero emissions by mid-century or earlier. Chapter 3 identifies climate change risks and impacts to which the world would need to adapt to, during these transitions and additional risks and impacts during potential 1.5°C overshoot pathways. The feasibility of these pathways is contingent upon systemic change (Section 4.3) and enabling conditions (Section 4.4), incuding policy packages. This section assesses the feasibility of options (technologies, actions and measures) that form parts of global systems under transition that make up 1.5°C-consistent pathways (Section 4.3).

Following the assessment framework developed in Chapter 1, economic and technological; institutional and socio-cultural; and environmental and geophysical feasibility are considered, and applied in to system transitions (Sections 4.3.1–4.3.4), overarching adaptation options (Section 4.3.5) and to Carbon Dioxide Removal (CDR) options (Section 4.3.7). This is done to assess the multi-dimensuional feasibility of mitigation and adaptation options that have seen considerable development and change since AR5. In the case of adaptation, the assessed AR5 options are typically clustered, for example, all options related to energy infrastructure resilience, independently of the generation source, are categorised as 'resilience of power infrastructure'.

Table 4.10 presents sets of indicators against which the multi-dimensional feasibility of individual adaptation options relevant to limiting warming of 1.5°C, and mitigation options along 1.5°C-consistent pathways, are assessed.

Table 4.10: Sets of indicators against which the feasibility of adaptation and mitigation are assessed, for each feasibility dimension (in Sections 4.3.1-4.3.4, 4.3.5 and 4.3.7)

	Characteristics	Adaptation indicators	Mitigation indicators
	Economic	Micro-economic viability Macro-economic viability Socio-economic vulnerability reduction potential Employment & productivity enhancement potential	Cost-effectiveness Absence of distributional effects Employment & productivity enhancement potential
	Technological	Technical resource availability Risks mitigation potential	Technical scalability Maturity Simplicity Absence of risk
	Institutional	Political acceptability Legal & regulatory feasibility Institutional capacity & administrative feasibility Transparency & accountability potential	Political acceptability Legal & administrative feasibility Institutional capacity Transparency & accountability potential
	Socio-cultural	Social co-benefits (health, education) Socio-cultural acceptability Social & regional inclusiveness Intergenerational equity	Social co-benefits (health, education) Public acceptance Social & regional inclusiveness Intergenerational equity Human capabilities

	Environmental/ecological	Ecological capacity Adaptive capacity/ resilience building potential	Reduction of air pollution Reduction of toxic waste Reduction of water use Improved biodiversity
	Geophysical	Physical feasibility Land use change enhancement potential Hazard risk reduction potential	Physical feasibility (physical potentials) Limited use of land Limited use of scarce (geo)physical resources Global spread

The feasibility assessment takes the following steps. First, each of the mitigation and adaptation options is assessed along the relevant indicators grouped around six feasibility dimensions: economic, technological, institutional, socio-cultural, environmental/ecological and geophysical. Three types feasibility groupings were assessed from the underlying literature: first, if the indicator could block the feasibility of this option, second, if the indicator has neither a positive, nor a negative effect on the feasibility of the option or the evidence is mixed, and third if the indicator does not pose any barrier to the feasibility of this option. The full assessment of each option under each indicator, including the literature references on which the assessment is based, can be found in supplementary materials D.2 and D.3. When appropriate, it is indicated that there is no evidence (NE), limited evidence (LE) or that the indicator is not applicable to the option (NA).

Next, for each feasibility dimension and option, the overall feasibility for a given dimension is assessed as the mean of combined scores of the relevant underlying indicators, and classified into 'insignificant barriers' (2.5 to 3), 'mixed or moderate but still existent barriers' (1.5 to 2.5) or 'significant barriers' (below 1.5) to feasibility. Indicators assessed as NA, LE or NE are not included in this overall assessment (see supplementary material D.1 for the averaging and weighing guidance).

The results are summarised in Table 4.11 (for mitigation options) and Table 4.12 (for adaptation options) for each of the six feasibility dimensions: where dark shading indicates few feasibility barriers; moderate shading indicates that there are some barriers and light shading that multiple barriers, in this dimension, may block implementation.

A three-step process of independent validation and discussion by authors and reviewers was undertaken to make this assessment as robust as possible within the scope of this special report. It must however, be recognised that this is an indicative assessment at global scale, and both policy and implementation at regional, national and local level would need to adapt and build on this knowledge, within the particular local context and constraints.

4.5.2 Implementing Mitigation

This section builds on the insights on mitigation options in Section 4.3, applies the assessment methodology along feasibility dimensions and indicators explained in Section 4.5.1, and synthesises the assessment of the enabling conditions in Section 4.4.

4.5.2.1 Assessing of Mitigation Options for Limiting Warming to 1.5˚C Against Feasibility Dimensions

An assessment of the degree to which examples of 1.5°C-relevant mitigation options face barriers to implementation, and on which contexts this depends, is summarised in Table 4.11. An explanation of the approach is given in Section 4.5.1 and in supplementary material D.1. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments. The detailed assessment and the literature underpinning the assessment can be found in supplementary material D.2.

The feasibility framework in Cross-Chapter Box 3 in Chapter 1 highlights that the feasibility of mitigation and adaptation options depends on many factors. Many of those are captured in the indicators in Table 4.10, but many depend on the specific context in which an option features. Since this Special Report did not have the mandate, space nor the literature base to undertake a regionally specific assessment. Hence the assessment is caveated as providing a broad indication of where the global barriers are likely to ignoring significant regional diversity. Regional and context-specific literature is also just emerging as recorded in knowledge gaps (Section 4.6). Nevertheless, in Table 4.11, an indicative attemot has been made to capture some relevant contextual information. The ‘context’ column indicates what contextual factors may affect the feasibility of an option, including regional differrences. For instance, solar irradiation in an area impacts the cost-effectiveness of solar Photovoltaic (PV), so solar irradiation is mentioned in this column.

Table 4.11: Feasibility assessment of examples of 1.5°C-relevant mitigation options with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading that on average, the dimension does not have a positive, nor a negative effect on the feasibility of the option, and faint shading the presence of potentially blocking barriers. No shading means that not sufficient literature could be found to make the assessment. Evidence and agreement assessment is undertaken at the option level. The context column on the far right indicates how the assessment might change if contextual factors are different. For the methodology and literature basis, see supplementary material D.1 and D.2.

System	Mitigation option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy system transitions	Wind energy (on-shore & off-shore)	Robust	Medium							Wind regime, economic status, space for windfarms and enhanced by legal framework for independent power producers affect uptake; cost-effectiveness affected by incentive regime.
	Solar PV	Robust	High							Cost-effectiveness affected by solar irradiation and incentive regime. Also enhanced by legal framework for independent power producers affect uptake.
	Bioenergy	Robust	Medium							Depends on availability of biomass and land and capability to manage sustainable land use. Distributional effects depend on the agrarian (or other) system used to produce feedstock.
	Electricity storage	Robust	High							Batteries universal but grid flexible resources vary with area's level of development
	Power sector CCS	Robust	High							Varies with local CO2 storage capacity, presence of legal framework, level of development and quality of public engagement
	Nuclear energy	Robust	High							Electricity market organisation, legal framework, standardisation & know-how, country's 'democratic fabric', institutional and technical capacity, and safety culture of public and private institutions
Land & ecosystem transitions	Reduced food wastage & efficient food production	Robust	High							Will depend on the combination of individual and institutional behaviour
	Dietary shifts	Medium	High							Depends on individual behaviour, education, cultural factors and institutional support
	Sustainable intensification of agriculture	Medium	High							Depends on development and deployment of new technologies
	Ecosystems restoration	Medium	High							Depends on location and institutional factors
Urban	Land-use & urban planning	Robust	Medium							Varies with urban fabric, not geography or economy; requires capacitated local government and legitimate tenure system

	Electric cars and buses	Medium	High							Varies with degree of government intervention; requires capacity to retrofit “fuelling” stations
	Sharing schemes	Limited	Medium							Historic schemes universal new ones depend on ICT status; undermined by high crime and low levels of law enforcement
	Public transport	Robust	Medium							Depends on presence of existing ‘informal’ taxi systems, which may be more cost effective and affordable than capital intensive new build schemes, as well as (local) government capabilities
	Non-motorised transport	Robust	High							Viability rests on linkages with public transport, cultural factors, climate and geography
	Aviation & shipping	Medium	Medium							Varies with technology, governance and accountability
	Smart Grids	Medium	Medium							Varies with economic status and presence or quality of existing grid
	Efficient appliances	Medium	High							Adoption varies with economic status and policy framework
	Low/zero-energy buildings	Medium	High							Depends on size of existing building stock and growth of building stock
Industrial system transitions	Energy efficiency	Robust	High							Potentials and adoption depends on existing efficiency, energy prices and interest rates, as well as government incentives.
	Bio-based & circularity	Medium	Medium							Faces barriers in terms of pressure on natural resources and biodiversity. Product substitution depends on market organisation and government incentivisation.
	Electrification & hydrogen	Medium	High							Depends on availability of large-scale, cheap, emission-free electricity (electrification, hydrogen) or CO2 storage nearby (hydrogen). Manufacturers' appetite to embrace disruptive innovations
	Industrial CCUS	Robust	High							High concentration of CO2 in exhaust gas improve economic and technical feasibility of CCUS in industry. CO2 storage or reuse possibilities.
Carbon dioxide removal	BECCS	Robust	Medium							Depends on biomass availability, CO2 storage capacity, legal framework, economic status and social acceptance
	DACCS	Medium	Medium							Depends on CO2-free energy, CO2 storage capacity, legal framework, economic status and social acceptance
	Afforestation & reforestation	Robust	High							Depends on location, mode of implementation, and economic and institutional factors

	Soil carbon sequestration & biochar	Robust	High							Depends on location, soil properties, time span
	Enhanced weathering	Medium	Low							Depends on CO2-free energy, economic status and social acceptance

4.5.2.2 Enabling Conditions for Implementation of Mitigation Options Towards 1.5˚C

The feasibility assessment highlights six dimensions that could help inform an agenda that could be addressed by the areas discussed in Section 4.4: governance, behaviour and lifestyles, innovation, enhancing institutional capacities, policy and finance. For instance, Section 4.4.3 on behaviour offers strategies for addressing public acceptance problems, and how changes can be more effective when communication and the actions relate to people's values. This section synthesises the findings in Section 4.4 in an attempt to link them to the assessment in Table 4.11. The literature on which the discussion is based is found in Section 4.4.

From Section 4.4, including the case studies presented in the Boxes 4.1 to 4.10, several main messages can be constructed. For instance, governance would have to be multi-level and engaging different actors, while being efficient, and choosing the type of cooperation based on the specific systemic challenge or option at hand. If institutional capacity for financing and governing the various transitions is not urgently built, many countries would lack the ability to change pathways from a high-emission scenario to a low- or zero-emission scenario. In terms of innovation, governments, both national and multilateral, can contribute to the mitigation-purposed application of general purpose technologies. If this is not managed, some emission reduction could happen autonomously, but it may not lead to a 1.5ºC-consistent pathway. International cooperation on technology, including technology transfer where this does not happen autonomously, is needed and can help creating the innovation capabilities in all countries to be able to operate, maintain, adapt and regulate a portfolio of mitigation technologies. Case studies in the various sub-sections highlight the opportunities and challenges of doing this in practice. They indicate that it can be done in specific circumstances .

A combination of behaviour-oriented pricing policies and financing options can help change technologies and social behaviour as it challenges the existing, high-emission socio-technical regime on multiple levels across feasibility characteristics. For instance, for dietary change, a combination of supply-side measures with value-driven communication and economic instruments may help make a lasting transition, while only an economic instrument, such as enhanced prices or taxation, may not be as robust.

Governments could benefit from enhanced carbon prices, as a price and innovation incentive and also source of additional revenue to correct distributional effects and subsidise the development of new, cost-effective negative-emission technology and infrastructure. However, there is *high evidence* and *medium agreement* that pricing alone is insufficient. Even if prices rise significantly, they typically incentivise incremental change, but typically fail to provide the impetus for private actors to take the risk of engaging in the transformational changes that would be needed to limit warming to 1.5ºC. Apart from the incentives to change behaviour and technology, financial systems are an indispensable element of a systemic transition. If financial markets do not acknowledge climate risk and the risk of transitions, they could be organised by regulatory financial institutions, such as central banks.

Strengthening implementation revolves around more than addressing barriers to feasibility. A system transition, be it in energy, industry, land or a city, requires changing the core parameters of a system. These relate, as introduced in Section 4.2 and further elaborated in Section 4.4, to how actors cooperate, how technologies are embedded, how resources are linked, how cultures relate and what values people associate with the transition and the current regime.

4.5.3 Implementing Adaptation

Article 7 of the Paris Agreement provides an aspirational global goal for adaptation, of 'enhancing adaptive capacity, strengthening resilience, and reducing vulnerability' (UNFCCC, 2015). Adaptation implementation is gathering momentum in many regions, guided by national NDC's and National Adaptation Plans (see Cross-Chapter Box 11 in this Chapter).

Operationalising adaptation in a set of regional environments on pathways to a 1.5°C world, requires strengthened global and differentiated regional and local capacities. It also needs rapid and decisive adaptation actions to reduce the costs and magnitude of potential climate impacts (Vergara et al., 2015).

This could be facilitated by: i) enabling conditions, especially improved governance, economic measures and financing (Section 4.4); ii) enhanced clarity on adaptation options to help identify strategic priorities, sequencing and timing of implementation (Section 4.3); iii) robust monitoring and evaluation frameworks; and iv) political leadership (Magnan et al., 2015; Magnan and Ribera, 2016; Lesnikowski et al., 2017; UNEP, 2017a).

4.5.3.1 Feasible Adaptation Options

This section summarises the feasibility (defined in Cross-Chapter Box 3, Table 1 in Chapter 1 and Table 4.4) of select adaptation options using evidence presented across this chapter and in supplementary material D.3 and the expert-judgement of its authors (Table 4.12). The options assessed respond to risks and impacts identified in Chapter 3. They were selected based on options identified in AR5 (Noble et al., 2014), focusing on those relevant to 1.5°C-compatible pathways, where sufficient literature exists. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments.

Besides gaps in the literature around crucial adaptation questions on the transition to a 1.5°C world (Section 4.6), there is inadequate current literature to undertake a spatially differentiated assessment (Cross-Chapter Box 3 in Chapter 1). There are also limited baselines for exposure, vulnerability and risk to help policy and implementation prioritisation. Hence, the compiled results can at best provide a broad framework to inform policymaking. Given the bottom-up nature of most adaptation implementation evidence, care needs to be taken in generalising these findings.

Options are considered as part of a systemic approach, recognising that no single solution to exits to limit warming to 1.5°C and adapting to its impacts. To respond to the local and regional context, and synergies and trade-offs between adaptation, mitigation and sustainable development, packages of options suited to local enabling conditions, can be implemented.

Table 4.12 summarises the feasibility assessment through its six dimensions with levels of evidence and agreement, and indicates how the feasibility of an adaptation option may be differentiated by certain contextual factors (last column).

Table 4.12: Feasibility assessment of examples of 1.5°C-relevant adaptation options with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading that on average, the dimension does not have a positive, nor a negative effect on the feasibility of the option, and light shading the presence of potentially blocking barriers. No shading means that not sufficient literature could be found to make the assessment. NA signifies that the dimension is not applicable to that adaptation option. For methodology and literature basis, see supplementary material D.

System	Adaptation option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy system transitions	Power infrastructure, including water	Medium	High							Depends on existing power infrastructure, all generation sources and with intensive water requirements
Land & ecosystem transitions	Conservation agriculture	Medium	Medium							Depends on irrigated/rainfed system, ecosystem characteristics, crop type, other farming practices
	Efficient irrigation	Medium	Medium							Depends on agricultural system, technology used, regional institutional and biophysical context
	Efficient livestock	Limited	High							Dependent on livestock breeds, feed practices,and biophysical context (e.g. carrying capacity)
	Agroforestry	Medium	High							Depends on knowledge, financial support, and market conditions
	Community-based adaptation	Medium	High							Focus on rural areas and combined with ecosystems-based adaptation, does not include urban settings
	Ecosystem restoration & avoided deforestation	Robust	Medium							Mostly focused on existing and evaluated REDD+ projects
	Biodiversity management	Medium	Medium							Focus on hotspots of biodiversity vulnerability and high connectivity
	Coastal defense & hardening	Robust	Medium							Depends on locations that require it as a first adaptation option
	Sustainable aquaculture	Limited	Medium							Depends on locations at risk and socio-cultural context
Urban & infrastructure system transitions	Sustainable land-use & urban planning	Medium	Medium							Depends on nature of planning systems and enforcement mechanisms
	Sustainable water management	Robust	Medium							Balancing sustainable water supply and rising demand especially in low-income countries
	Green infrastructure & ecosystem services	Medium	High							Depends on reconciliation of urban development with green infrastructure

	Building codes & standards	Limited	Medium							Adoption requires legal, educational, and enforcement mechanisms to regulate buildings
Industrial system transitions	Intensive industry infrastructure resilience and water management	Limited	High							Depends on intensive industry, existing infrastructure and using or requiring high demand of water
Overarching adaptation options	Disaster risk management	Medium	High							Requires institutional, technical, and financial capacity in frontline agencies and government
	Risk spreading and sharing	Medium	Medium							Requires well developed financial structures and public understanding
	Climate services	Medium	High							Depends on climate information availability and usability, local infrastructure and institutions, national priorities
	Indigenous knowledge	Medium	High							Dependent on recognition of Indigenous rights, laws, and governance systems
	Education and learning	Medium	High							Existing education system, funding
	Population health and health system	Medium	High							Requires basic health services and infrastructure
	Social safety nets	Medium	Medium							Type and mechanism of safety net, political priorities, institutional transparency
	Human migration	Medium	Low							Hazard exposure, political and socio-cultural acceptability (in destination), migrant skills and social networks

When considered jointly, the description of adaptation options (Section 4.3), the feasibility assessment (summarised in Table 4.12), and discusson of enabling conditions (Section 4.4) show us how options can be implemented and lead towards transformational adaptation if and when needed.

The adaptation options for energy system transitions focus on existing power infrastructure resilience and water management, when required, for any type of generation source. These options are not sufficient for the far-reaching transformations required in the energy sector, which have tended to focus on technologies to shift from a fossil-based to a renewable energy system (Erlinghagen and Markard, 2012; Muench et al., 2014; Brand and von Gleich, 2015; Monstadt and Wolff, 2015; Child and Breyer, 2017; Hermwille et al., 2017). There is also need for integration of this with social-ecological systems transformations to increase the resilience of the energy sector, for which appropriate enabling conditions, such as for technological innovations, are fundamentally important. Institutional capacities can be enhanced by expanding the role of actors as transformation catalysts (Erlinghagen and Markard, 2012). The integration of ethics and justice within these transformations can help attain the SDG7 on clean energy access (Jenkins et al., 2018), while inclusion of the cultural dimension and cultural legitimacy (Amars et al., 2017) can provide a more substantial base for societal transformation. Strengthening policy instruments and regulatory frameworks and enhancing multi-level governance that focusses on resilience components can help secure these transitions (Exner et al., 2016).

For land and ecosystem transitions, conservation agriculture, efficient irrigation, agroforestry, ecosystem restoration and avoided deforestation, and coastal defence and hardening have between *medium and robust evidence* with *medium to high agreement*. The other options assessed have limited or no evidence across one or more of the feasibility dimensions. Community-based adaptation is assessed as an option many opportunities with *medium evidence* and *high agreement* though faces scaling barriers. Given the structural changes these options may require, transformational adaptation may be implied in some regions, involving enhanced multi-level governance and institutional capacities by enabling anticipatory and flexible decision-making systems that access and develop collaborative networks (Dowd et al., 2014), tackling root causes of vulnerability (Chung Tiam Fook, 2017), and developing synergies between development and climate change (Burch et al., 2017). Case studies show the use of transformational adaptation approaches for fire management (Colloff et al., 2016a), floodplain and wetland management (Colloff et al., 2016b), and forest management (Chung Tiam Fook, 2017), in which the strengthening of policy instruments and climate finance are also required.

There is growing recognition of the need for transformational adaptation within the agricultural sector but limited evidence on how to facilitate processes of deep, systemic change (Dowd et al., 2014). Case studies demonstrate that transformational adaptation in agriculture requires a sequencing and overlap between incremental and transformational adaptation actions (Hadarits et al., 2017; Termeer et al., 2017), e.g., incremental improvements to crop management while new crop varieties are being researched and field tested (Rippke et al., 2016). Broader considerations include addressing stakeholder values and attitudes (Fleming et al., 2015a), understanding and leveraging the role of social capital, collaborative networks, and information (Dowd et al., 2014), and being inclusive with rural and urban communities, and the social, political, and cultural environment (Rickards and Howden, 2012). Transformational adaptation in agriculture systems could have significant economic and institutional costs (Mushtaq, 2016), along with potential unintended negative consequences (Davidson, 2016; Rippke et al., 2016; Gajjar et al., 2018; Mushtaq, 2018), and a need to focus on the transitional space between incremental and transformational adaptation (Hadarits et al., 2017), as well as the timing of the shift from one to the other (Läderach et al., 2017).

Within urban and infrastructure transitions, green infrastructure and sustainable water management are assessed as the most feasible options, followed by sustainable land-use and urban planning. The need for transformational adaptation in urban settings arises from the root causes of poverty, failures in sustainable development, and a lack of focus on social justice (Revi et al., 2014a; Parnell, 2015; Simon and Leck, 2015; Shi et al., 2016; Ziervogel et al., 2016a; Burch et al., 2017), with the focus on governance structures and the inclusion of equity and justice (Bos et al., 2015; Shi et al., 2016; Hölscher et al., 2018).

Current implementation of Urban Ecosystems-based Adaptation (EbA) lacks a systems perspective of transformations and consideration of the normative and ethical aspects of EbA (Brink et al., 2016). Flexibility within urban planning could help deal with the multiple uncertainties of implementing adaptation (Radhakrishnan et al., 2018) (Rosenzweig and Solecki, 2014), for example, urban adaptation pathways were implemented in the aftermath of Hurricane Sandy in New York, which is considered as tipping point that led to the implementation of transformational adaptation practices.

Adaptation options for industry focus on infrastructure resilience and water management. Like with energy system transitions, technological innovation would be required, but also the enhancement of institutional capacities. Recent research illustrates transformational adaptation within industrial transitions focusing on the role of different actors and tools driving innovation, and points to the role of Nationally Appropriate Mitigation Actions in avoiding lock-ins and promoting system innovation (Boodoo and Olsen, 2017), the role of private sector in sustainability governance in the socio-political context (Burch et al., 2016), and of green entrepreneurs driving transformative change in the green economy (Gibbs and O'Neill, 2014). (Lim-Camacho et al., 2015) suggest an analysis of the complete lifecycle of supply chains as a means of identifying additional adaptation strategies, as opposed to the current focus on a part of the supply chain. Chain-wide strategies can modify the rest of the chain and present a win-win with commercial objectives.

The assessed adaptation options also have mitigation synergies and tradeoffs (assessed in Section 4.5.4) that need to be carefully considered, while planning climate action.

4.5.3.2 Monitoring and Evaluation

Monitoring and Evaluation (M&E) in adaptation implementation can promote accountability and transparency of adaptation financing, facilitate policy learning and the share good practices, pressure laggards, and guide adaptation planning. The majority of research on M&E focuses on specific policies or programmes, and has typically been driven by the needs of development organisations, donors, and governments to measure the impact and attribution of adaptation initiatives (Ford and Berrang-Ford, 2016). There is growing research examining adaptation progress across nations, sectors, and scales (Austin et al. 2016; Heidrich et al. 2016; Lesnikowski et al. 2016; Reckien et al. 2014; Robinson 2017; Araos et al. 2016a,b). Responding to need for global, regional and local adaptation, developing indicators and standardised approaches to evaluate and compare adaptation over time and across regions, countries, and sectors would enhance comparability and learning. A number of constrains continue to hamper progress on adaptation M&E, including a debate on what actually constitutes adaptation for purposes of assessing progress (Dupuis and Biesbroek 2013; Biesbroek et al. 2015), absence of comprehensive and systematically collected data on adaptation to support longitudinal assessment and comparison (Lesnikowski et al. 2016; Ford et al. 2015), lack of agreement on indicators to measure (Lesnikowski et al. 2015; Bours et al. 2015; Brooks et al. 2013), and challenges of attributing altered vulnerability to adaptation actions (UNEP 2017; Bours et al. 2015; Ford et al. 2013).

4.5.4 Synergies and Trade-Offs Between Adaptation and Mitigation

Implementing a particular mitigation or adaptation option may affect the feasibility and effectiveness of other mitigation and adaptation options. Supplementary Material E.1 provides examples of possible positive impacts (synergies) and negative impacts (trade-offs) of mitigation options for adaptation. For example, renewable energy sources such as wind energy and solar PV combined with electricity storage can increase resilience due to distributed grids, thereby enhancing both mitigation and adaptation. Yet, as another example, urban densification may reduce Greenhouse Gas (GHG) emissions, enhancing mitigation, but can also intensify heat island effects and inhibit restoration of local ecosystems if not accounted for, thereby increasing adaptation challenges.

The table in Supplementary Material E.2 provides examples of synergies and trade-offs of adaptation options for mitigation. It shows, for example, that conservation agriculture can reduce some GHG emissions and thus enhance mitigation, but at the same time increase other GHG emissions thereby reducing mitigation potential. As another example, agroforestry can reduce GHG emissions through reduced deforestation and fossil fuel consumption, but has a lower carbon sequestration potential compared with natural and secondary forest.

Maladaptive actions could increase the risk of adverse climate-related outcomes, for example, biofuel targets could lead to indirect land use change and influence local food security, through a shift in land use abroad in response to increased domestic biofuel demand, increasing global GHG emissions, rather than decreasing it.

Various options enhance both climate change mitigation and adaptation, and would hence serve two 1.5°C-related goals: reducing emissions while adapting to the associated climate change. Examples of such options are reforestation, urban and spatial planning, and land and water management.

Synergies between mitigation and adaptation may be enhanced, and trade-offs reduced, by considering enabling conditions (Section 4.4), while trade-offs can be amplified when enabling conditions are not considered (C.A. Scott et al., 2015). For example, information that is tailored to the personal situation of individuals and communities, including climate services, that are credible and targeted at the point of decision making, can enable and promote both mitigation and adaptation actions (Section 4.4.3). Similarly, multi-level governance and community participation, respectively, can enable and promote both adaptation and mitigation actions (Section 4.4.1). Governance, policies and institutions can facilitate the implementation of the Water-Energy-Food (WEF) nexus (Rasul and Sharma, 2016). The WEF can enhance food, water and energy security, particularly in cities with agricultural production areas (Biggs et al., 2015), electricity generation with intensive water requirements (Conway et al 2015), and in agriculture (El Gafy et al., 2017) and livelihoods (Biggs et al., 2015). Such a nexus approach can reduce the transport energy that is embedded in food value chains (Villarroel Walker et al., 2014), providing diverse sources of food in the face of changing climates (Tacoli et al., 2013). Urban agriculture, where integrated, can mitigate climate change and support urban flood management (Angotti, 2015; Bell et al., 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lwasa et al., 2015; Y.C.E. Yang et al., 2016; Sanesi et al., 2017). In the case of electricity generation, enabling conditions through a combination of carefully selected policy instruments can maximize the synergic benefits between low GHG energy production and water for energy (Shang et al., 2018). Despite the multiple benefits of maximising synergies between mitigation and adaptations options through the WEF nexus approach (Chen and Chen, 2016), there are implementation challenges given institutional complexity, political economy, and interdependencies between actors (Leck et al., 2015).

[START BOX 4.10 HERE]

Box 4.10: Bhutan: Synergies and Trade-Offs in Economic Growth, Carbon Neutrality and Happiness

Bhutan has three national goals, improving: its Gross National Happiness Index (GNHI), economic growth (Gross Domestic Product, GDP) and carbon neutrality. These goals increasingly interact and raise questions about whether they can be sustainably maintained into the future. Interventions in this enabling environment are required to comply with all three goals.

Bhutan is well known for its GNHI, which is based on a variety of indicators covering psychological well-being, health, education, cultural and community vitality, living standards, ecological issues and good governance (RGoB, 2012; Schroeder and Schroeder, 2014; Ura, 2015). The GNHI is a precursor to the Sustainable Development Goals (SDGs) (Allison, 2012; Brooks, 2013) and reflects local enabling environments. The GNHI has been measured twice, in 2010 and 2015, and this showed an increase of 1.8% (CBS, 2016). Like most emerging countries, Bhutan wants to increase its wealth and become a middle-income country (RGoB, 2013, 2016), while it remains carbon-neutral, a goal which has been in place since 2011 at COP 19 and was reiterated in its Intended Nationally Determined Contribution (NEC, 2015). Bhutan achieves its current carbon-neutral status through hydropower and forest cover (Yangka and Diesendorf, 2016) which are part of their resilience and adaptation strategy.

Nevertheless, Bhutan faces rising Greenhouse Gas (GHG) emissions. Transport and industry are the largest growth areas (NEC, 2011). Bhutan's carbon-neutral status would be threatened by 2037 by business-as-usual approaches to economic growth (Yangka and Newman, 2018). Increases in hydropower are being planned based on climate change scenarios that suggest sufficient water supply will be available (NEC, 2011). Forest cover is expected to remain sufficient to maintain co-benefits. The biggest challenge is to electrify both freight and passenger transport (ADB, 2013). Bhutan wants to be a model for achieving economic growth consistent with limiting climate change to 1.5°C and improving its Gross National Happiness (Michaelowa et al., 2018) through synthesizing all three goals and improving its adaptive capacity.

[END BOX 4.10 HERE]

4.6 Knowledge Gaps and Key Uncertainties

The global response to limiting warming to 1.5°C is a new knowledge area, that has emerged after the Paris Agreement. This sections presents a number of knowledge gaps that have emerged from the assessment of mitigation, adaptation and Carbon Dioxide Removal (CDR) options and Solar Radiation Modification (SRM) measures, enabling conditions, and synergies and tradeoffs. Illustrative questions that emerge synthesising the more comprehensive Table 4.14 below include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (CBDR-RC), reciprocity and partnership? To what extent limit warming to 1.5°C needs a harmonization of macro-financial and fiscal policies, that could include Central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives?

These knowledge gaps are highlighted in Table 4.13 along with a cross-reference to the respective sections in the last column.

Table 4.13: Knowledge gaps and uncertainties

Knowledge area		***Mitigation***	***Adaptation***	***Reference***
1.5°C pathways and ensuing change		• Lack of literature specific to 1.5°C on investment costs with detailed breakdown by technology. • Lack of literature specific to 1.5°C on mitigation costs in terms of GDP and welfare. • Lack of literature on distributional implications of 1.5°C compared to 2°C or business-as-usual at sectoral and regional levels. • Limited 1.5°C-specific case studies for mitigation • Limited knowledge on the systemic and dynamic aspects of transitions to 1.5°C, including how vicious or virtuous circles might work, how self-reinforcing aspects can be actively introduced and managed.	• Lack of literature specific to 1.5°C on adaptation costs and need • Lack of literature on what overshoot means for adaptation • Lack of knowledge on avoided adaptation investments associated with limiting warming to 1.5°C, 2°C or business-as-usual • Limited 1.5°C-specific case studies for adaptation • Scant literature examining current or future adaptation options, or examining what different climate pathways mean for adaptation success • Need for transformational adaptation at 1.5°C and beyond remains largely unexplored	4.2
Options to achieve and	Energy	• The shift to variable renewables that many countries are implementing is just reaching a level where large-scale storage systems or other grid	• Relatively little literature on individual adaptation options since AR5	4.3.1

adapt to 1.5°C		flexibility options, e.g., demand response, are required to enable resilient grid systems, thus, new knowledge on the opportunities and issues associated with scaling up zero carbon grids would be needed including knowledge about how zero carbon electric grids can integrate with the full scale electrification of transport systems. • CCS suffers mostly from uncertainty about the feasibility of timely upscaling, both due to lack of regulatory capacity and concerns about storage safety and cost. • There is not much literature on the distributional implications of large-scale bioenergy deployment, the assessment of environmental feasibility is hampered by a diversity of contexts of individual studies (type of feedstock, technology, land availability), which could be improved through emerging meta-studies	• No evidence on socio-cultural acceptability of adaptation options • Lack of regional research on the implementation of adaptation options.	
	Land & ecosystems	• More knowledge would be needed on how land-based mitigation can be reconciled with land demands for adaptation and development. • While there is now more literature on the underlying mechanisms of land transitions, data is often insufficient to draw robust conclusions, and uncertainty about land availability • The lack of data counts on social and institutional information (largest knowledge gap indicated for ecosystems restoration in Table 4.11), which is therefore not widely integrated in land use modelling. • Examples of successful policy implementation and institutions related to land-based mitigation leading to co-benefits for adaptation and development are missing from the literature	• Regional information on some options does not exist, especially in the case of land use transitions. • Limited research examining socio-cultural perspectives and impacts of adaptation options, especially for efficient irrigation, coastal defense and hardening, agroforestry and biodiversity management • Lack of longitudinal, regional studies assessing the impacts of certain adaptation options such as conservation agriculture and shifting to efficient livestock systems. • More knowledge is needed on the cost-effectiveness and scalability of various adaptation options. For example, there is no evidence for the macro-economic viability of Community-based Adaptation (CbA) and biodiversity management, nor on employment and productivity enhancement	4.3.2

		• There is relatively little scientific literature on the effects of dietary shifts and reduction of food wastage on mitigation, especially regarding the institutional, technical and environmental concerns	potential for biodiversity management and coastal defense and hardening. • More knowledge is needed on risk mitigation and the potential of biodiversity management. • Lack of evidence of the political acceptability of efficient livestock • Limited evidence on legal and regulatory feasibility of conservation agriculture and no evidence on coastal defense and hardening • For transparency and accountability potential, there is limited evidence for conservation agriculture and no evidence for biodiversity management, coastal defense and hardening and sustainable aquaculture • No evidence on hazard risk reduction potential of conservation agriculture and biodiversity management.	
	Urban systems & infrastructure	• Limited evidence of effective land use planning in low income cities where tenure and land zoning is contested, and the risks of trying to implement land use planning under communal tenure. • Limited evidence on the governance of public transport from an accountability and transparency perspective • Limited evidence on relationship between toxic waste and public transport. • Limited evidence on the impacts of electric vehicles and non-motorised urban transport as most schemes are too new. • As changes in shipping and aviation have been limited to date, limited evidence of social impacts. • Knowledge about how to facilitate disruptive, demand-based innovations that may be transformative in urban systems, is needed.	• Regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses of households, across time and space. • More knowledge is needed on the political economy of adaptation, particularly on how to impute different types of cost and benefit in a consistent manner, on adaptation performance indicators that could stimulate investment, and the impact of adaptation interventions on socio-economic, and other types, of inequality. • More evidence would be needed on hot-spots, for example the growth of peri-urban areas populated by large informal settlements. • Major uncertainties emanate from the lack of knowledge on the integration of climate adaptation and mitigation, disaster risk management, and urban poverty alleviation. • There is limited evidence on the institutional, technological and economic feasibility of green	4.3.3

		• The urban form implications of combined changes from electric, autonomous and shared/public mobility systems, is needed. • Considering distributional consequences of climate responses is an on-going need. • Knowledge gaps in the application and scale-up of combinations of new smart technologies, sustainable design, advanced construction techniques and new insulation materials, renewable energy and behaviour change in urban settlements. • The potential for leapfrog technologies to be applied to slums and new urban developments in developing countries is weak.	infrastructure and environmental services and for socio-cultural and environmental feasibility of codes and standards • In general, there is no evidence for the employment and productivity enhancement potential of most adaptation options. • There is limited evidence on the economic feasibility of sustainable water management.	
	Industry	• Lack of knowledge on potential for scaling up and global diffusion of zero- and low-emission technologies in industry • Questions remain on the socio-cultural feasibility of industry options, including human capacity and private sector acceptance of new, radically different technologies from current well-developed practices, as well as distributional effects of potential new business models • As the industrial transition unfolds, lack of knowledge on its dynamic interactions with other sectors, in particular with the power sector (and infrastructure) for electrification of industry, with food production and other users of biomass in case of bio-based industry developments, and with CDR technologies in the case of CC(U)S. • Life-cycle assessment-based comparative analysis of CCUS options are missing, as well as life-cycle information on electrification and hydrogen. • Impacts of industrial system transitions are not well understood, especially on employment, identity and well-being, in particular in the case of substitution	• Very limited evidence on how industry would adapt to the consequences of 1.5 or 2°C temperature increases, in particular large and immobile industrial clusters in low-lying areas and availability of transportation and (cooling) water resources and infrastructure. • There is limited evidence on the economic, institutional and socio-cultural feasibility of adaptation options available to industry.	4.3.4

		of conventional , high-carbon industrial products with lower-carbon alternatives, as well as electrification and use of hydrogen.		
	Short-lived climate forcers	• Limited evidence of co-benefits and trade-offs of SLCF reduction (e.g., better health outcomes, agricultural productivity improvements). • Integration of SLCFs into emissions accounting and international reporting mechanisms enabling a better understanding of the links between black carbon, air pollution, climate change and agricultural productivity.		4.3.6
	CDR	• A bottom-up analysis of CDR options, indicates that there are still key uncertainties around the individual technologies. This – includes Ocean-based options will be assessed in depth in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Assessments of environmental aspects are missing, especially for 'newer' options like Enhanced Weathering or Direct Air Carbon Capture. • In order to obtain more information on realistically available and sustainable removal potentials, more bottom-up, regional studies, also taking into account also social issues, would be needed. These can better inform the modeling of 1.5°C pathways. • Knowledge gaps on issues of governance and public acceptance, the impacts of large-scale removals on the carbon cycle, the potential to accelerate deployment and upscaling, and means of incentivisation. • Knowledge gaps on integrated systems of renewable energy and CDR technologies such as enhanced weathering and DACCS		4.3.7

		• Knowledge gaps on the use of captured CO_2 is generating negative emissions and as mitigation option.		
	Overarching Adaptation Options	• There is no evidence on technical and institutional feasibility of educational options • There is limited evidence on employment and productivity enforcement potential of climate services • There is limited evidence on socio-cultural acceptability of social safety nets • There is a small but growing literature on human migration as an adaptation strategy. Scant literature on the cost effectiveness of migration.		4.3.5
Enabling conditions	Governance	• As technological changes have begun to accelerate, there is lack of knowledge on new mechanisms that can enable private enterprise to mainstream this activity and reasons for success and failure need to be researched. • Research is thin on effective multi-level governance in particular in developing countries, including participation by civil society, women and minoritiesGaps in knowledge remain pertaining to partnerships within local governance arrangements that may act as mediators and drivers for achieving global ambition and local action. • Methods for assessing contribution and aggregation of non-state actors in limiting warming to 1.5°C • Knowledge gap on an enhanced framework for assessment of the ambition of NDCs	• The ability to identify explanatory factors affecting the progress of climate policy is constrained by a lack of data on adaptation actions across nations, regions, and sectors, compounded by an absence of frameworks for assessing progress. Most hypotheses on what drives adaptation remain untested. • Limited empirical assessment of how governance affects adaptation across cases • Focus on 'success' stories and leading adaptors overlooks lessons from situations where no or unsuccessful adaptation is taking place	4.4.1
	Institutions	• Lack of 1.5°C-specific literature • Role of regulatory financial institutions and their capacity to guarantee financial stability of economies when investments potentially face risks both because of climate impacts and because of the systems transitions if lower temperature scenarios are pursued. • Knowledge gaps on how to build capabilities across all countries and regions globally to implement, maintain, manage, govern and further develop mitigation options for 1.5°C. • While importance of Indigenous and local knowledge is recognized, the ability to scale up beyond the local remains challenging and little examined • There is a lack of monitoring and evaluation (M&E) of adaptation measures, with most studies enumerating M&E challenges and emphasising the importance of context and social learning. Very few studies evaluate		4.4.2

		whether and why an adaptation initiative has been effective. One of the challenges of M&E for both mitigation and adaptation is a lack of high quality information for modellings. Adaptation M&E is additionally challenged by limited understanding on what indicators to measure and how to attribute altered vulnerability to adaptation actions.		
	Lifestyle and behavioural change	• Whereas mitigation pathways studies address (implicitly or explicitly) the reduction or elimination of market failures (e.g., external costs, information asymmetries) *via* climate or energy policies, no study addresses behavioural change strategies in the relationship with mitigation and adaptation actions in the 1.5°C context. • Limited knowledge on GHG emission reduction potential of diverse mitigation behaviour across the world. • Most studies on factors enabling lifestyle changes have been conducted in high income countries, more knowledge needed from low- and middle-income countries, and the focus in typically on enabling individual behavior change, far less on enabling change in organisations and political systems • Limited understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways, e.g., in Integrated Assessment Models.	• Knowledge gaps on factors enabling adaptation behaviour, except for behaviour in agriculture. • Little is known about cognitive and motivational factors promoting adaptive behavior. • Little is known about how potential adaptation actions might affect behavior to influence vulnerability outcomes	4.4.3
		Lack of insight on what can enable changes in adaptation and mitigation behaviour in organisations and political systems.		
	Technological innovation	• Quantitative estimates for mitigation and adaptation potentials at economy or sector scale as a result of the combination of general purpose technologies and mitigation technologies have been scarce, except for some evidence in the transport sector. • Evidence on the role of international organisations, including the UNFCCC, in building capabilities and enhancing technological innovation for 1.5°C, except for some parts of the transport sector. • Technology transfer trials to enable leapfrog applications in developing countries have limited evidence		4.4.4
	Policy	• More empirical research would be needed to derive robust conclusions on effectiveness of policies for	• Understanding of what polices work (and do not work) is limited for adaptation in general and for	4.4.5

		enabling transition to 1.5°C and on which factors aid decision-makers seeking to ratchet up their NDCs	1.5°C in particular, beyond specific case studies.	
	Finance	Knowledge gaps persist with respect to the instruments to match finance to its most effective use in mitigation and adaptation.		4.4.5
Synergies and tradeoffs between adaptation and mitigation		• Strong claims are made with respect to synergies and trade-offs, but there is little knowledge to underpin these, especially of co-benefits by region. • Water-energy conservation relationships of individual conservation measures in industries other than the water and energy sectors have not been investigated in detail. • There is no evidence on synergies with adaptation of CCS in the power sector and of enhanced weathering under carbon dioxide removal. • There is no evidence on trade-offs with adaptation of low and zero-energy buildings, and circularity and substitution and bio-based industrial system transitions. • There is no evidence of synergies or trade-offs with mitigation of CbA • There is no evidence of trade-offs with mitigation of the built environment, on adaptation options for industrial energy, and climate services		4.5.4
SRM		• In spite of increasing attention to the different SRM measures and their potential to keep global temperature below 1.5°C, knowledge gaps remain not only with respect to the physical understanding of SRM options, but also concerning ethical issues. • We do not know how to govern SRM in order to avoid unilateral action and how to prevent possible reductions in mitigation ('moral hazard').		4.3.8

Frequently Asked Questions

FAQ 4.1: What transitions could enable limiting global warming to 1.5°C?

***Summary**: In order to limit warming to 1.5°C above preindustrial levels, the world would need to transform in a number of complex and connected ways. While transitions towards lower greenhouse gas emissions are underway in some cities, regions, countries, businesses and communities, there are few that are currently consistent with limiting warming to 1.5°C. Meeting this challenge would require a rapid escalation in the current scale and pace of change, particularly in the coming decades. There are many factors that affect the feasibility of different adaptation and mitigation options that could help limit warming to 1.5°C and adapting to the consequences.*

There are actions across all sectors can substantially reduce greenhouse gas emissions. This Special Report assesses energy, land and ecosystems, urban and infrastructure, and industry in developed and developing nations to see how they would need to be transformed to limit warming to 1.5°C. Examples of actions include shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing 'green infrastructure', such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities.

Because these different actions are connected, a 'whole systems' approach would be needed for the type of transformations that could limit warming to 1.5°C. This means that all relevant companies, industries and stakeholders would need to be involved to increase the support and chance of successful implementation. As an illustration, the deployment of low-emission technology (e.g., renewable energy projects or a bio-based chemical plants) would depend upon economic conditions (e.g., employment generation or capacity to mobilise investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding).

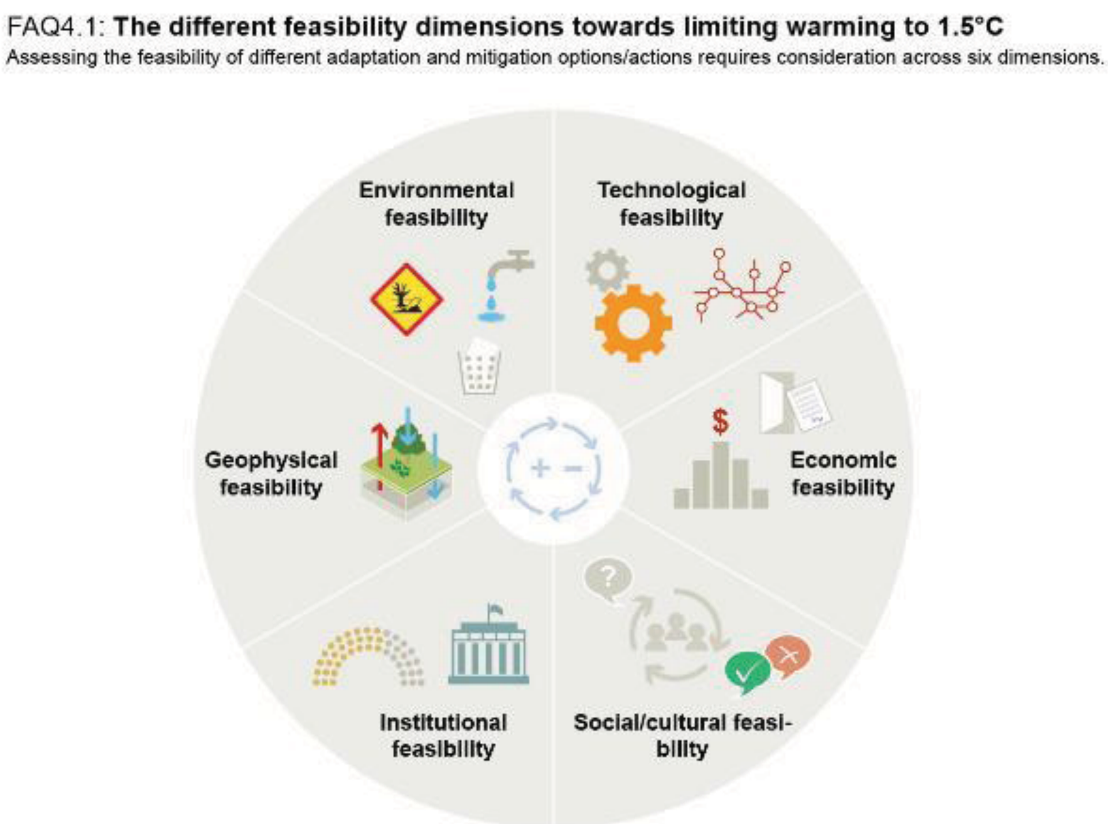
To limit warming to1.5°C, mitigation would have to be large-scale and rapid. Transitions can be transformative or incremental, and they often, but not always, go hand in hand. Transformative change can arise from growth in demand for a new product or market, such that it displaces an existing one. This is sometimes called 'disruptive innovation'. For example, high demand for LED lighting is now making more energy-intensive, incandescent lighting near-obsolete, with the support of policy action that spurred rapid industry innovation. Similarly, smart phones have become global in use within ten years. But electric cars, which were released around the same time, have not been adopted so quickly because the bigger, more connected transport and energy systems are harder to change. Renewable energy, especially solar and wind, is considered to be disruptive by some as it is rapidly being adopted and is transitioning faster than predicted. But its demand is not yet uniform. Urban systems that are moving towards transformation are coupling solar and wind with battery storage and electric vehicles in a more incremental transition, though this would still require changes in regulations, tax incentives, new standards, demonstration projects and education programmes to enable markets for this system to work.

Transitional changes are already underway in many systems but limiting warming to 1.5°C would require a rapid escalation in the scale and pace of transition, particularly in the next 10-20 years. While limiting warming to 1.5°C would involve many of the same types of transitions as limiting warming to 2°C, the pace of change would need to be much faster. While the *pace* of change that would be required to limit warming to 1.5°C can be found in the past, there is no historical precedent for the *scale* of the necessary transitions, in particular in a socially and economically sustainable way. Resolving such speed and scale issues would require people's support, public-sector interventions and private-sector cooperation.

Different types of transitions carry with them different associated costs and requirements for institutional or governmental support. Some are also easier to scale up than others, and some need more government support than others. Transitions between, and within, these systems are connected and none would be sufficient on its own to limit warming to 1.5°C.

The 'feasibility' of adaptation and mitigation options or actions within each system that together can limit warming to 1.5°C within the context of sustainable development and efforts to eradicate poverty requires careful consideration of multiple different factors. These factors include: (i) whether sufficient natural systems and resources are available to support the various options for transitioning (known as *environmental feasibility*); (ii) the degree to which the required technologies are developed and available (known as *technological feasibility*); (iii) the economic conditions and implications (known as *economic feasibility*); (iv) what are the implications for human behaviour and health (known as *social/cultural feasibility*); and (v) what type of institutional support would be needed, such as governance, institutional capacity and political support (known as *institutional feasibility*). An additional factor (vi - known as the *geophysical feasibility*) addresses the capacity of physical systems to carry the option, for example whether it is geophysically possible to implement large-scale afforestation consistent with 1.5°C.

Promoting enabling conditions, such as finance, innovation and behaviour change, would reduce barriers to the options, make the required speed and scale of the system transitions more likely, and therefore would increase the overall feasibility limiting warming to 1.5°C.



FAQ4.1, Figure 1: The different dimensions to consider when assessing the 'feasibility' of adaptation and mitigation options or actions within each system that can help to limit warming to 1.5°C. These are: (i) the environmental feasibility; (ii) the technological feasibility; (iii) the economic feasibility; (iv) the social/cultural feasibility; (v) the institutional feasibility; and (vi) the geophysical feasibility.

FAQ 4.2: What are Carbon Dioxide Removal and negative emissions?

Summary: *Carbon Dioxide Removal (CDR) refers to the process of removing CO_2 from the atmosphere. Since this is the opposite of emissions, practices or technologies that remove CO_2 are often described as achieving 'negative emissions'. The process is sometimes referred to more broadly as Greenhouse Gas Removal if it involves removing gases other than CO_2. There are two main types of CDR: either enhancing existing natural processes that remove carbon from the atmosphere (e.g., by increasing its uptake by trees, soil, or other 'carbon sinks') or using chemical processes to, for example, capture CO_2 directly from the ambient air and storing it elsewhere (i.e., underground). All CDR methods are at different stages of development and some are more conceptual than others, as they have not been tested at scale.*

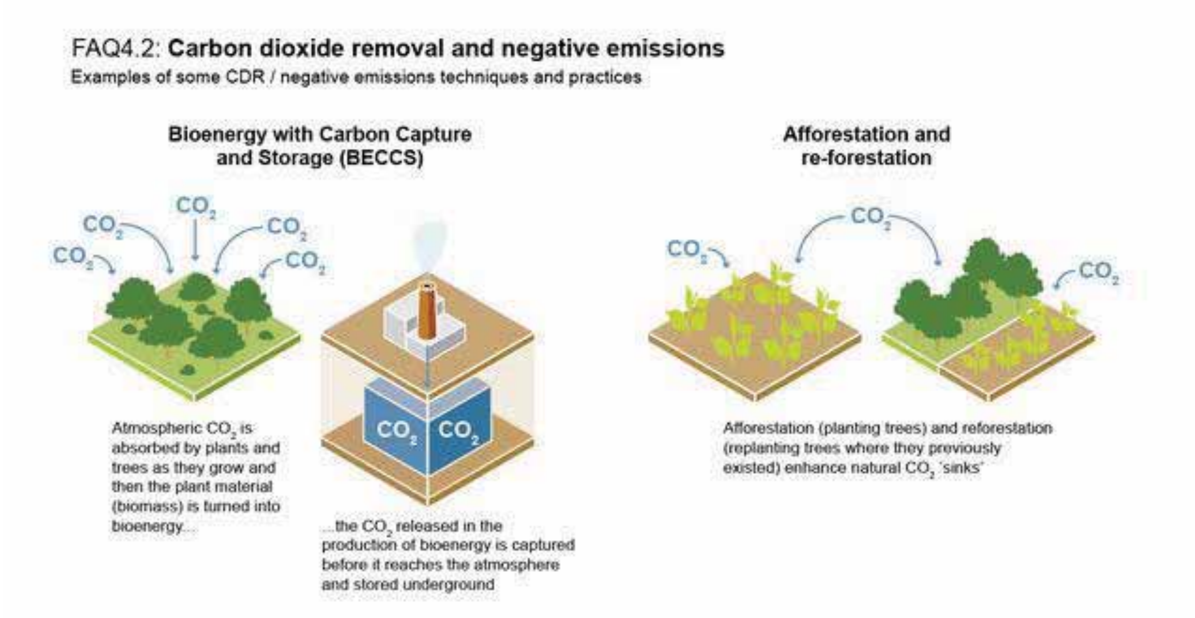
Limiting warming to 1.5°C above preindustrial levels would require unprecedented rates of transformation in many areas, including in the energy and industrial sectors, for example. Conceptually, it is possible that techniques to draw CO_2 out of the atmosphere (known as Carbon Dioxide Removal, or CDR) could contribute to limiting warming to 1.5°C. One use of CDR could be to compensate for greenhouse gas emissions from sectors that cannot completely decarbonise, or which may take a long time to do so.

If global temperature temporarily overshoots 1.5°C, CDR would be required to reduce the atmospheric concentration of CO_2 to bring global temperature back down. To achieve this temperature reduction, the amount of CO_2 drawn out of the atmosphere would need to be greater than the amount entering the atmosphere, resulting in 'net negative emissions'. This would involve a greater amount of CDR than stabilising atmospheric CO_2 concentration – and, therefore, global temperature – at a certain level. The larger and longer an overshoot, the greater the reliance on practices that remove CO_2 from the atmosphere.

There are a number of CDR methods, each with different potentials for achieving negative emissions, as well as different associated costs and side effects. They are also at differing levels of development, with some more conceptual than others. One example of a CDR method in the demonstration phase is a process known as Bioenergy with Carbon Capture and Storage (BECCS), in which atmospheric CO_2 is absorbed by plants and trees as they grow and then the plant material (biomass) is burned to produce bioenergy. The CO_2 released in the production of bioenergy is captured before it reaches the atmosphere and stored in geological formations deep underground on very long timescales. Since the plants absorb CO_2 as they grow and the process does not emit CO_2, the overall effect can be to reduce atmospheric CO_2.

Afforestation (planting new trees) and reforestation (replanting trees where they previously existed) are also considered forms of CDR because they enhance natural CO_2 'sinks'. Another category of CDR techniques uses chemical processes to capture CO_2 from the air and store it away on very long timescales. In a process known as Direct Air Carbon Capture and Storage (DACCS), CO_2 is extracted directly from the air and stored in geological formations deep underground. Converting waste plant material into a charcoal-like substance called biochar and burying it in soil can also be used to store carbon away from the atmosphere for decades to centuries.

There can be beneficial side effects of some types of CDR, other than removing CO_2 from the atmosphere. For example, restoring forests or mangroves can enhance biodiversity and protect against flooding and storms. But there could also be risks involved with some CDR methods. For example, deploying BECCS at large scale would require a large amount of land to cultivate the biomass required for bioenergy. This could have consequences for sustainable development if the use of land competes with producing food to support a growing population, biodiversity conservation, or land rights. There are also other considerations. For example, there are uncertainties about how much it would cost to deploy DACCS as a CDR technique, given that removing CO_2 from the air requires considerable energy.



FAQ4.2, Figure 1: Carbon Dioxide Removal (CDR) refers to the process of removing CO_2 from the atmosphere. Thereare a number of CDR techniques, each with different potential for achieving 'negative emissions', as well as different associated costs and side effects.

FAQ 4.3: Why is adaptation important in a 1.5°C warmer world?

***Summary**: Adaptation is the adjustment process to current or expected changes in climate and its effects. Even though climate change is a global problem, its impacts are experienced differently across the world. This means that responses are often specific to the local context, and so people in different regions are adapting in different ways. A rise in global temperature from 1°C to 1.5°C, and beyond, increases the need for adaptation. Therefore, stabilising global temperatures at 1.5°C above pre-industrial levels would require a smaller adaptation effort than for 2°C. Despite many successful examples around the world, progress in adaptation is, in many regions, in its infancy and unevenly distributed globally.*

Adaptation refers to the process of adjustment to actual or expected changes in climate and its effects. Since different parts of the world are experiencing the impacts of climate change differently, there is similar diversity in how people in a given region are adapting to those impacts.

The world is already experiencing the impacts from 1°C of global warming above preindustrial levels and there are many examples of adaptation to impacts associated with this warming. Examples of adaptation efforts taking place around the world include investing in flood defences such as building sea walls or restoring mangroves, efforts to guide development away from high risk areas, modifying crops to avoid yield reductions, and using social learning (social interactions that changes understanding on the community level) to modify agricultural practices, amongst many others. Adaptation also involves building capacity to respond better to climate change impacts, including making governance more flexible and strengthening financing mechanisms such as providing different types of insurance.

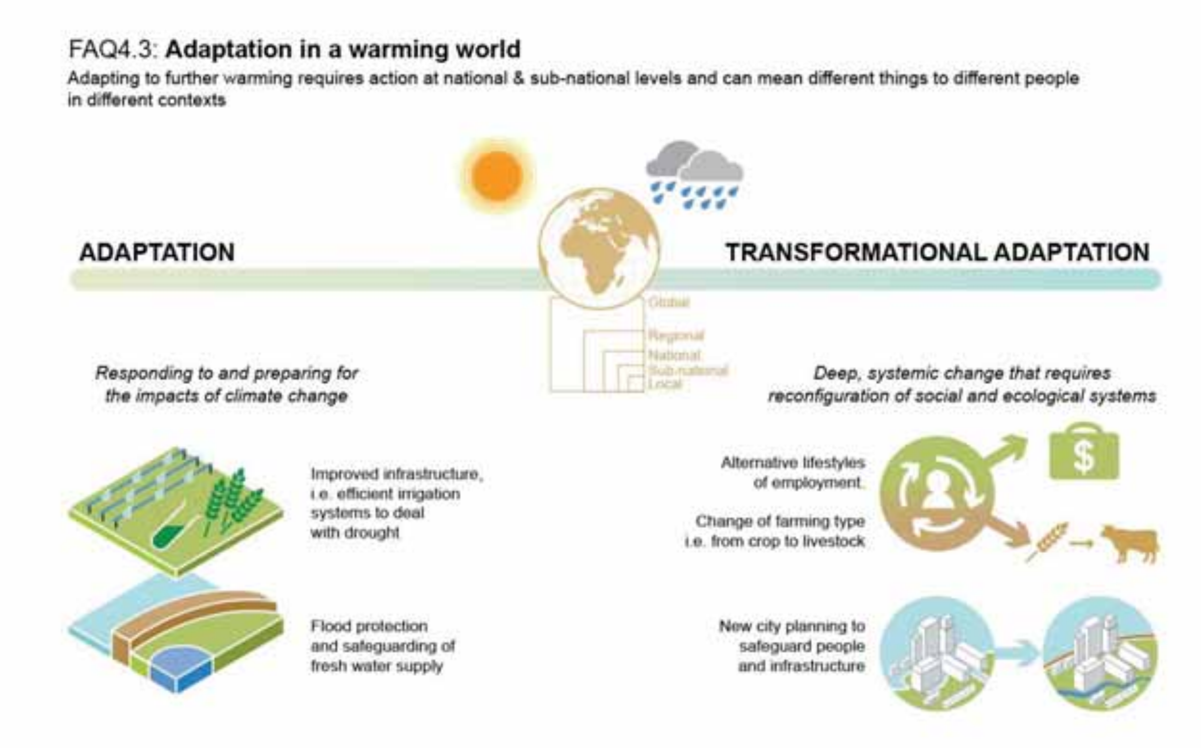
In general, an increase in global temperature from present day to 1.5°C or 2°C (or higher) above preindustrial temperatures would increase the need for adaptation. Therefore, stabilising global temperature increase at 1.5°C would require a smaller adaptation effort than for 2°C.

Since adaptation is still in early stages in many regions, this raises questions about the capacity of vulnerable communities to cope with any amount of further warming. Successful adaptation can be supported at the national and sub-national levels, with national governments playing an important role in coordination, planning, determining policy priorities, and distributing resources and support. Given that the need for adaptation can be very different from one community to the next, the kinds of measures that can successfully reduce climate risks will also depend heavily on the local context.

When done successfully, adaptation can allow individuals to adjust to the impacts of climate change in ways that minimise negative consequences and maintain their livelihoods. This could involve, for example, a farmer switching drought-tolerant crops to deal with increasing occurrences of heat waves. In some cases, however, the impacts of climate change could result in entire systems changing significantly, such as moving to an entirely new agricultural system in areas where the climate is no longer suitable for current practices. Constructing sea walls to stop flooding due to sea level rising from climate change is another example of adaptation, but developing city planning to change how flood water is managed throughout the city would be an example of transformational adaptation. These actions require significantly more institutional, structural, and financial support. While this kind of transformational adaptation wouldn't be needed everywhere in a 1.5°C world, the scale of change needed would be challenging to implement, as it requires additional support such as through financial assistance and behavioural change. Few empirical examples exist to date.

Examples from around the world show that adaptation is an iterative process. Adaptation pathways describe how communities can make decisions about adaptation in an ongoing and flexible way. Such pathways allow for pausing, evaluating the outcomes of specific adaptation actions, and modifying the strategy as appropriate. Due to their flexible nature, adaptation pathways can help to identify the most effective ways to minimise the impacts of present and future climate change for a given local context. This is important since adaptation can sometimes exacerbate vulnerabilities and existing inequalities if poorly designed. The unintended negative consequences of adaptation that can sometimes occur is known as 'maladaptation'. Maladaptation can be seen if a particular adaptation option has negative consequences for some (e.g., rainwater harvesting upstream might reduce water availability downstream) or if an adaptation intervention in the present has trade-offs in the future (e.g., desalination plants may improve water availability in the present but have large energy demands over time).

While adaptation is important to reduce the negative impacts from climate change, adaptation measures on their own are not enough to prevent climate change impacts entirely. The more global temperature rises, the more frequent, severe, and erratic the impacts will be, and adaptation may not protect against all risks. Examples of where limits may be reached include substantial loss of coral reefs, massive range losses for terrestrial species, more human deaths from extreme heat, and losses of coastal-dependent livelihoods in low lying islands and coasts.



FAQ4.3, Figure 1: Examples of adaptation and transformational adaptation. Adapting to further warming requires action at national & sub-national levels and can mean different things to different people in different contexts. While transformational adaptation wouldn't be needed everywhere in a world limited to 1.5°C warming, the scale of change needed would be challenging to implement.

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