the Yurok Tribe, the Gila River Indian Community, and the Tohono O'odham Nation are among the first tribes in the region to develop climate adaptation and resilience plans, which reflects a nationwide gap or need for further tribal adaptation plan development. Lack of capacity and funds has hindered progress in moving from planning to implementation, which is similar to the situation for U.S. cities.[497]

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting Indigenous peoples in the Southwest include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) the way snow is treated in regional modeling,[498] 3) variability in projections of extreme precipitation, and, in particular, 4) uncertainties in summer and fall precipitation projections for the region.[88] Additional uncertainties exist in sea level rise projections[242] and, for the California coast, ocean process model projections of acidification, deoxygenation, and warming coastal zone temperatures.[499] For the most part, Native lands lack instrumental monitoring for weather and climate, which is a barrier for long-term climate-related planning.[493]

Complexities arising from the multiple factors affecting ecosystem processes, including tree mortality and fire, often preclude formal detection and attribution studies. Much evidence and agreement among evidence exist regarding the role of hotter temperatures in fire and tree mortality.[7,146] Detection and attribution studies seldom focus explicitly on tribal lands.

Other uncertainties relate to estimating future vulnerabilities and impacts, which depend, in part, on adjudication of unresolved water rights and the potential development of local, state, regional, tribal, and national policies that may promote or inhibit the development and deployment of adaptation and mitigation strategies.

Description of confidence and likelihood

The documented human-caused increase in temperature is a key driver of regional impacts to snow, soil moisture, forests, and wildfire, which affect Indigenous peoples, other frontline communities, and all of civil society. Case study evidence, using Indigenous and Western scientific observations, oral histories, traditional knowledge and wisdom (e.g., Ferguson et al. 2016[493]), suggests that climate change is affecting the health, livelihoods, natural and cultural resources, practices, and spiritual well-being of Indigenous communities and peoples in the Southwest (e.g., Redsteer et al. 2011, 2013; Wotkyns 2011; Cozzetto et al. 2013; Gautam et al. 2013; Navajo Nation Department of Fish and Wildlife 2013; Nania and Cozzetto et al. 2014; Sloan and Hostler 2014; Redsteer and Fordham 2017[44,302,305,307,310,311,490,500,501]). Abundant evidence gives *high confidence* that hotter temperatures, tree mortality, and increased wildfire and drought, due to climate change, would disrupt the ecosystems on which Indigenous people depend; the likelihood of these impacts affecting individual tribes will depend in large part on the non-climatic stresses (such as historical legacies and resource management practices) interacting with the climatic stresses. *Very high confidence* exists that tribes are developing adaptation measures and emissions reductions to address current and future climate change, based on abundant ongoing initiatives and associated documentation.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures (*very likely*, *very high confidence*). Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely*, *high confidence*).

Description of evidence base

Numerous studies link Southwest hydrologic drought with a decline in renewable hydroelectricity generation in the region. Hydroelectric generation depends on runoff to fill reservoirs to maximize generation capacity.[336,337] During the California drought, which was intensified by climate change,[14,56] hydroelectric generation in California fell from 43 trillion watt-hours (TWh) in 2011 before the drought to 14 TWh in 2015 during the drought.[335] Climate change also reduced the snowpack[46,47,48,49] and river runoff on which hydroelectric generation depends.[336,337]

Similarly, low reservoir levels in Lake Mead—which is formed by damming the Colorado River—driven by reduced Colorado River runoff[13,59] can reduce the efficiency and production levels of hydropower at Hoover Dam.

Fossil fuel generation efficiency depends on the temperature and availability of the external cooling water. Warming could reduce energy efficiency up to 15% across the Southwest by 2100.[91] Higher temperatures also increase electric resistance in transmission lines, causing transmission losses of 7% under higher emissions.[344] Replacing fossil fuel generation with solar power renewables reduces greenhouse gas emissions and water use per unit of electricity generated.[90] This supports the assertion that increasing solar energy generation in the Southwest could meet the energy demand no longer being met by hydropower and fossil fuel as well as the expected increase in energy use in the future.

Solar energy production is also an economic opportunity for the region. The energy potential for renewable energy is estimated to range from one-third to over ten times 2013 generation levels from all sources.[502] The lower range assumes capacity requirements remain at 2013 levels,[502] but recent data show an upward trend in Southwest energy use.[89]

The high potential for solar energy projects in the Southwest and the extent of federally owned land in the Southwest (well over half the total surface area for the six-state region) prompted the Bureau of Land Management (BLM) and the U.S. Department of Energy to conduct a programmatic environmental impact analysis of a new Solar Energy Program to further support utility-scale solar energy development on BLM-administered lands.[502,503] This potential capacity, combined with the increasingly competitive cost of solar and wind,[504] presents economic opportunities for the region and an opportunity to reduce overall greenhouse gas emissions.

Solar and renewable energy jobs are increasing. The solar workforce increased 25% in 2016, while wind employment increased 32%.[505] Jobs in low-carbon-emission generation systems, including renewables, nuclear, and advanced low-emission natural gas, comprise 45% of all the jobs in the electric power generation and fuels technologies.[505] Growing Southwest energy use, competitive prices for renewables, and the renewable energy potential of the Southwest favor the replacement of fossil-fuel-generated energy by renewable solar and wind energy.

Major uncertainties

Climate model projections of the future diverge on whether precipitation may increase or decrease for much of the region, so hydroelectric power changes may exhibit spatial variation. The amount of runoff is a key factor driving the generation potential for hydroelectric power. A key uncertainty is how much hydroelectricity generation will decline. Some projections of higher-than-average precipitation in the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.[105]

Energy demand in the Southwest is increasing, but the rate of growth is uncertain.[506] Changes in energy market prices cause future uncertainty in the future mix of energy sources for the Southwest.[502] The low cost of natural gas and the competitive cost of solar and wind renewables make it somewhat certain the proportion of the energy generated from these sources will continue to increase and offset reductions in traditional fossil-fuel-generated energy, reducing overall greenhouse gas emissions.[504] Renewable energy job growth potential is also uncertain and depends on the factors mentioned above.[505]

Additionally, daily to multiyear variation in coastal cloud cover affects solar electricity generation potential along the California coast.[507,508,509,510]

Description of confidence and likelihood

Hydrological drought in California reduced hydroelectric generation[335] and fossil fuel electricity generation efficiencies. Drought and rising temperatures under climate change can reduce the ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest (*very likely, very high confidence*). Renewable solar and wind energy offers increased electricity reliability, lower water intensity for energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely, high confidence*).

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages (*medium confidence*). Increased drought, heat waves, and reduction of winter chill hours can harm crops (*medium confidence*) and livestock (*high confidence*); exacerbate competition for water among agriculture, energy generation, and municipal uses (*medium confidence*); and increase future food insecurity (*medium confidence*).

Description of evidence base

Climate change has altered climate factors fundamental to food production and rural livelihoods in the Southwest. Abundant evidence and good agreement in evidence exist regarding regionally increasing temperatures, reduced soil moisture, and effects on regional snowpack and surface water sources.[13,23,67,74,79] The heat of climate change has intensified severe droughts in California[14,56] and the Colorado River Basin.[13] Hotter temperatures and aridity in the Southwest affected agricultural productivity from 1981 to 2010.[366]

Elevated temperatures can be associated with failure of some crops, such as warm-season vegetable crops, and reduced yields and/or quality in others.[374] Temperatures in California, Nevada, and Arizona are already at the upper threshold for corn[372] and rice.[373] While crops grown in some areas might not be viable under hotter conditions, other crops such as olives, cotton, kiwi, and oranges may replace them.[375] In the Southwest, climate change may cause a northward shift in crop production, potentially displacing existing growers and affecting rural communities.[376] Quality of specialty crops, both nutritive and sensory, declines because of increased temperatures and other changes associated with a changing climate,[393,511] which is particularly important in a region producing a majority of the Nation's specialty crops. Decreases in winter chill hours may reduce fruit and tree nut yields, though the magnitude may vary considerably.[380,381]

High ambient temperatures associated with climate change could decrease production of rangeland vegetation across the Southwest,[384] reducing available forage for livestock. Ranching enterprises across the region have vastly different characteristics that will influence their adaptive capacities.[390]

Local-scale impacts can vary considerably across the region depending upon surface and groundwater availability. Drought causes altered water management, with heavy reliance on a limited groundwater to sustain regional food production.[130] Despite severe localized impacts, losses in total agricultural revenue are buffered by groundwater reliance to offset surface water shortage.[369] Parts of the Southwest have exhausted sustainable use of groundwater resources. When surface water supplies are reduced, farmers shift to increased groundwater pumping, even when pumping raises production costs[371]—declining groundwater tables significantly increase pumping costs and require drilling of deeper wells.[130] Continued climate change may reduce aquifer recharge in the southern part of the region 10%–20%.[370] Climate change is projected to cause longer and more severe drought periods that will intensify the uncertainty associated with Southwest water supply and demand. Water-intensive forage crops and the livestock industry are especially vulnerable to climate-related water shortages.[15]

Major uncertainties

The impacts of climate change on food production depend upon microclimatology and local-scale environmental, social, and economic resources. While the scientific community relies upon computer models and generalized information to project likely future conditions, unforeseen consequences of warming temperatures, such as those related to pests, pollinators, and pathogens, may be more detrimental than some of the well-documented projections, such as temperature impacts on reduced yields. The effects of increased precipitation supplying the deep root zone may somewhat offset the increase in temperature, so agricultural drought may be less frequent for trees and other crops dependent on deeper soil moisture.[480] Scientists are producing more drought- and heat-tolerant cultivars, which may be suitable to production in the projected warmer and more arid climate of the Southwest.

Since food security relies on complex national and international trade networks, how regional climate change may affect local food security is uncertain. Many adaptation options, such as using alternate breeds, crops, planting and harvest dates, and new (sometimes untested) chemicals, may work in certain situations but not others. Thus, predicting impacts to food production in a hotter/drier land is likely to vary by crop and location, necessitating flexibility and adaptive management. Of paramount uncertainty is the impact of water shortage on regional food production as other uses may outcompete producers for limited supplies.

Description of confidence and likelihood

Since the availability of affordable food around the world depends upon complex trade and transportation networks, the effects of climate change on Southwest food availability, production, and affordability remain highly complex and thereby uncertain and classified with *medium confidence*. While the viability of rural livelihoods is vulnerable to water shortages and other climate-related risks, rural livelihoods may be supplemented by other nonagricultural income, such as recreation and hunting. The viability of rural livelihoods is highly complex, and risk is, therefore, classified with *medium confidence*. Crop impacts related to hotter and drier conditions and reduced winter chill periods, caused by climate change, are classified with *medium confidence*. Not all crops are directly harmed by warming temperatures, and the simulation impacts of reduced chilling hours can produce a fairly wide range of results depending upon model assumptions. Hotter and drier conditions can directly harm livestock via reduced forage quantity and quality and exposure to higher temperatures, conferring a *high confidence* classification. Projections of future drought and water scarcity portend increased competition for water from other beneficial uses with *medium confidence*.

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread (*high confidence*). Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change (*medium confidence*).

Description of evidence base

Strong evidence and good agreement among multiple sources and lines of evidence exist, indicating that the Southwest regional temperature may increase, snowpack may decline, soil moisture may decrease, and drought may be prolonged.[14,23,24,56,58,62,68,74,480]

Exposure to hotter temperatures and extreme heat events, partly a manifestation of human-caused climate change, already led to heat-associated deaths and illnesses in heat waves in Arizona and California in the early and mid-2000s.[398,399,400,401,402,406,444,450,512]

Good agreement exists among models that most of the Southwest may become more arid, due to the effect of increasing temperatures on snow, evaporation, and soil moisture.[58,65,70,80] Projections also indicate that flood-causing atmospheric rivers may become more moist, frequent, and intense[84,85,86] and that intense daily precipitation may increase in frequency.[88,513] Models project declines in future runoff of key Southwest rivers, such as the Colorado, due chiefly to the effects of increased temperature on soil moisture and snowpack.[13,71,110]

Strong evidence exists of the effects of extreme heat on public health in the region (e.g., Knowlton et al. 2009, Oleson et al. 2015, Wilhelmi et al. 2004[400,514,515]) and for reasonable projections of future deaths and costs of lost labor productivity due to enhanced future episodes of extreme heat. Factors that predict a person will be at increased risk include being confined to bed, not leaving home daily, and being unable to care for oneself;[516] various general indicators of being socially isolated (such as living alone, the presence of or frequency of social contacts, or being isolated linguistically);[516,517,518,519] and persons who are socioeconomically disadvantaged.[516,517,518,519] Dehydration in general and dehydration associated with medications (neurological and non-neurological) that impair thermoregulation or thirst regulation were also associated with elevated risk of mortality during the 2003 heat wave in France.[520] The role of prescription medications in altering the risk for heat-associated illness or death is of growing interest and concern.[521] This issue is more important as chronic diseases become more prevalent and more people take prescription drugs.

Given the proportion of the U.S. population in the Southwest, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.[158,420] West Nile virus transmission is projected to shift to the north under climate change, and areas where the mosquitoes that carry this virus are present may see increased abundances.[441,442,443] The mosquito species that carry Zika and chikungunya are established in parts of the region, but mosquito-borne transmission has only been observed in Puerto Rico, the U.S. Virgin Islands, Florida, and Texas (Ch. 14: Human Health).

Overall, the Southwest is ill-prepared to absorb the additional patient load that would accompany climate change associated disasters.[448] The American College of Emergency Physicians assigned an overall emergency care grade of C or C+ to three of the six Southwest states, with the others receiving poorer grades, and four of the six states received an F grade for access to emergency care.[448]

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting public health include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) variability in projections of extreme precipitation, 3) uncertainties in summer and fall precipitation projections for the region,[88] and 4) uncertainties in models that project occurrence and levels of climate-sensitive exposures that are known to impact public health, such as local and regional ozone air pollution, particulate air pollution (for example, increases from wildfire emissions or reductions from advancements in vehicle emissions control technology), or occurrence and exposure to toxins or pathogens.

Studies of non-fatal illnesses using healthcare services data can yield critical insights different from those one can derive from death data. Most studies of heat impacts on health have focused on deaths rather than nonfatal illnesses. This is primarily because hospitalization and emergency department data, compared with death certificate data, are not as available or uniform across locations, and when they are available it can be difficult to access them due to concerns for patient confidentiality. Ongoing enhancements to electronic medical records technology and adoption across the healthcare services sector will potentially address those limitations in the near future and will provide invaluable data resources to identify and adopt prevention strategies that reduce the vulnerability of patients and populations to the adverse effects of climate-sensitive exposures.

More recent work focusing on the more deadly neuroinvasive West Nile virus indicates that regionally, the central and southern parts of the country may experience increasing cost from this vector-borne disease in the future.[178,440] The lack of a statistical association between temperature and West Nile virus diagnoses in the Southwest may be because extreme temperatures in some locations rise above the survival thresholds for vectors, thereby reducing mosquito abundance[522,523] and disease transmission.[419] Additionally, because the data for diseases like Valley fever are limited to cases, rather than exposures, the link to climate change is not clear.[435,436]

While improvements to individual health and to clinical and community infrastructure are highly likely to 1) improve physical capacity to adapt to climate effects, 2) diminish the overall impacts on population health, and 3) increase societal capacity to respond quickly to dampen the effects of long-term and emergency responses,[446,447,524] other factors also influence adaptive capacity, adding considerable uncertainty. For example, many factors influence the observed number of West Nile virus cases including available habitat, human prevention and control efforts, and recent history of cases in a given area.[442,525,526,527]

Description of confidence and likelihood

Evaluation of confidence levels for the assessment of the type and magnitude of observed or projected public health and clinical impacts was based on the strength of evidence underlying the answers to three primary questions:

1. What characteristics of the region's historical climate and weather patterns translate directly (for example, extreme heat) or indirectly (for example, higher temperatures fostering ozone formation or the growth and spread of pathogens and vectors) to exposures associated with observed human health risks that are unique to or overrepresented in the Southwest?
2. Does recent historical evidence indicate that climate and weather patterns have changed, or do climate models project changes over the 21st century, thereby increasing the risk of human exposures and health impacts evaluated under question 1?
3. What are the determinants of individual and population vulnerability that increase or decrease the risk of an adverse health outcome or affect adaptive capacity? These include factors that affect a) biological susceptibility, b) physical environment and exposure characteristics, and c) social, behavioral, or economic factors.

To the extent possible, the evaluation recognized and accounted for the complex interconnections among these factors, the fact that their relative importance may differ across geographic and temporal scales, and the combined uncertainties of evidence from multiple disciplines (for example, health sciences, climatology, and social or behavioral sciences) that can vary substantially.

The information revealed by answering those questions, gives *high confidence* that extreme heat will be the dominant driver of exposures that pose the greatest health risks in the

Southwest—including direct effects of heat on individuals and indirect effects of heat on air pollution levels. Due to the uncertainties related to the frequency and intensity of human exposures and related to impacts on essential ecosystem services under projected climate change, the statement "Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change" is made with *medium confidence*. Nevertheless, clinical and public health policy effectiveness assessments show that such improvements can reduce the burden of disease and health risks associated with environmental exposures.

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26 Alaska

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26 Alaska

Anchorage, Alaska

Key Message 1

Marine Ecosystems

Alaska's marine fish and wildlife habitats, species distributions, and food webs, all of which are important to Alaska's residents, are increasingly affected by retreating and thinning arctic summer sea ice, increasing temperatures, and ocean acidification. Continued warming will accelerate related ecosystem alterations in ways that are difficult to predict, making adaptation more challenging.

Key Message 2

Terrestrial Processes

Alaska residents, communities, and their infrastructure continue to be affected by permafrost thaw, coastal and river erosion, increasing wildfire, and glacier melt. These changes are expected to continue into the future with increasing temperatures, which would directly impact how and where many Alaskans will live.

Key Message 3

Human Health

A warming climate brings a wide range of human health threats to Alaskans, including increased injuries, smoke inhalation, damage to vital water and sanitation systems, decreased food and water security, and new infectious diseases. The threats are greatest for rural residents, especially those who face increased risk of storm damage and flooding, loss of vital food sources, disrupted traditional practices, or relocation. Implementing adaptation strategies would reduce the physical, social, and psychological harm likely to occur under a warming climate.

Key Message 4

Indigenous Peoples

The subsistence activities, culture, health, and infrastructure of Alaska's Indigenous peoples and communities are subject to a variety of impacts, many of which are expected to increase in the future. Flexible, community-driven adaptation strategies would lessen these impacts by ensuring that climate risks are considered in the full context of the existing sociocultural systems.

Key Message 5

Economic Costs

Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska. It is also reducing heating costs throughout the state. These effects are very likely to grow with continued warming. Timely repair and maintenance of infrastructure can reduce the damages and avoid some of these added costs.

Key Message 6

Adaptation

Proactive adaptation in Alaska would reduce both short- and long-term costs associated with climate change, generate social and economic opportunity, and improve livelihood security. Direct engagement and partnership with communities is a vital element of adaptation in Alaska.

Executive Summary

Alaska is the largest state in the Nation, almost one-fifth the size of the combined lower 48 United States, and is rich in natural capital resources. Alaska is often identified as being on the front lines of climate change since it is warming faster than any other state and faces a myriad of issues associated with a changing climate. The cost of infrastructure damage from a warming climate is projected to be very large, potentially ranging from $110 to $270 million per year, assuming timely repair and maintenance. Although climate change does and will continue to dramatically transform the climate and environment of the Arctic, proactive adaptation in Alaska has the potential to reduce costs associated with these impacts. This includes the dissemination of several tools, such as guidebooks to support adaptation planning, some of which focus on Indigenous communities. While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

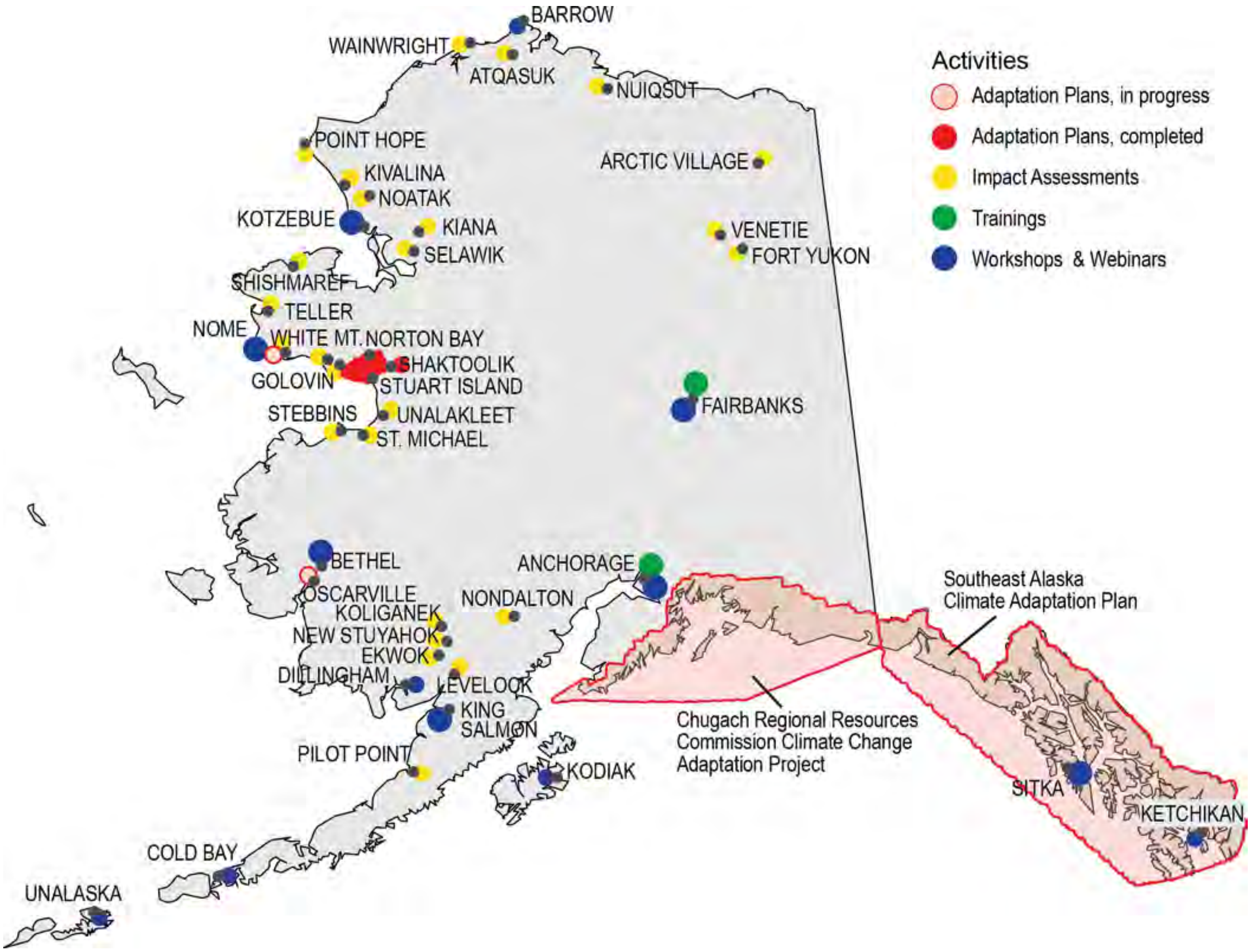
As the climate continues to warm, there is likely to be a nearly sea ice-free Arctic during the summer by mid-century. Ocean acidification is an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions and negatively affects organisms. Climate change will likely affect management actions and economic drivers, including fisheries, in complex ways. The use of multiple alternative models to appropriately characterize uncertainty in future fisheries biomass trajectories and harvests could help manage these challenges. As temperature and precipitation increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost is expected to continue, with associated impacts to infrastructure, river and stream discharge, water quality, and fish and wildlife habitat.

Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat in the future and in some cases requiring entire communities or portions of communities to relocate to safer terrain. The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States. Climate change exerts indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting disease ecology and food security, especially in rural communities. Alaska's rural communities are predominantly inhabited by Indigenous peoples who may be disproportionately vulnerable to socioeconomic and environmental change; however, they also have rich cultural traditions of resilience and adaptation. The impacts of climate change will likely affect all aspects of Alaska Native societies, from nutrition, infrastructure, economics, and health consequences to language, education, and the communities themselves.

The profound and diverse climate-driven changes in Alaska's physical environment and ecosystems generate economic impacts through their effects on environmental services. These services include positive benefits directly from ecosystems (for example, food, water, and other resources), as well as services provided directly from the physical environment (for example, temperature moderation, stable ground for supporting infrastructure, and smooth surface for overland transportation). Some of these effects are relatively assured and in some cases are already occurring. Other impacts are highly uncertain, due to their dependence on the structure of global and regional economies and future human alterations to the environment decades into the future, but they could be large.

In Alaska, a range of adaptations to changing climate and related environmental conditions are underway and others have been proposed as potential actions, including measures to reduce vulnerability and risk, as well as more systemic institutional transformation.

Adaptation Planning in Alaska



The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;[4] the University of Alaska for invasive species;[5] and the Alaska Native Tribal Health Consortium for local observations of environmental change.[6] Additional examples of community-based monitoring can be found through the website of the Alaska Ocean Observing System.[7] *From Figure 26.9 (Source: adapted from Meeker and Kettle 2017[8]).*

Background

Alaska is the largest state in the Nation, spanning a land area of around 580,000 square miles, almost one-fifth the size of the combined lower 48 United States. Its geographic location makes the United States one of eight Arctic nations. The State has an abundance of natural resources and is highly dependent on oil, mining, fishing, and tourism revenues. Changes in climate can have positive and negative impacts on these resources.[9,10,11]

As part of the Arctic, Alaska is on the front lines of climate change[12,13] and is among the fastest warming regions on Earth (Ch. 2: Climate, KM 7).[14] It is warming faster than any other state, and it faces a myriad of issues associated with a changing climate. The retreat of arctic sea ice affects many Alaskans in different ways, such as through changes in fish and wildlife habitat that are important for subsistence, tourism, and recreational activities.[15,16] The warming of North Pacific waters can contribute to the northward expansion of marine fish species, ecosystem changes, and potential relocation of fisheries.[17] An ice-free Arctic also contributes to increases in ocean acidification (through greater ocean–atmosphere interaction), affecting marine mammal habitat and the growth and survival of fish and crab species that are important for both personal and commercial use.[18] Lack of sea ice also contributes to increased storm surge and coastal flooding and erosion, leading to the loss of shorelines and causing some communities to relocate.[19]

Thawing permafrost, melting glaciers, and the associated effects on Alaska's infrastructure and hydrology are also of concern to Alaskans. Thawing permafrost has negatively affected important infrastructure, which is costly to repair, and these costs are projected to increase.[20,21] Melting glaciers may affect hydroelectric power generation through changes in river discharge and associated changes in reservoir capacity.[22] A warming climate is also likely to increase the frequency and size of wildfires, potentially changing the type and extent of wildlife habitat favorable for some important subsistence species.[23,24,25] Climate change also brings a wide range of human health threats to Alaskans due to increased injuries, smoke inhalation, damage to vital infrastructure, decreased food and water security, and new infectious diseases.[10] The subsistence activities of local residents are also affected, which in turn affects food security, culture, and health.[26,27,28,29]

The cost of a warming climate is projected to be huge, potentially ranging from $3 to $6 billion, between 2008 and 2030 (in 2008 dollars; $3.3–$6.7 billion in 2015 dollars). There are, however, a number of opportunities for Alaskans to respond to these climate-related challenges, including several tools and guidebooks available to support adaptation planning, with some focused specifically on Indigenous communities.[30] While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

Climate

The rate at which Alaska's temperature has been warming is twice as fast as the global average since the middle of the 20th century. Statewide average temperatures for 2014–2016 were notably warmer as compared to the last few decades,[31,32,33] with 2016 being the warmest on record. Daily record high temperatures in the contiguous United States are now occurring twice as often as record low temperatures. In Alaska, starting in the 1990s, high temperature records occurred three times as often as record lows, and in 2015, an astounding nine times as frequently.[34,35]

Statewide annual average temperatures from 1925 to the late 1970s were variable with no clear pattern of change;[36] however, beginning in the late 1970s and continuing at least through the end of 2016, Alaska statewide annual average temperatures began to increase, with an average rate of 0.7ºF per decade, (Taylor et al. 2017,[37] after Hartmann and Wendler 2005;[38] see Figure 26.1). Temperatures have been increasing faster in Arctic Alaska than in the temperate southern part of the state, with the Alaska North Slope warming at 2.6 times the rate of the continental U.S. and with many other areas of Alaska, most notably the west coast, central interior, and Bristol Bay, warming at more than twice the continental U.S. rate.[39] The long-term temperature trends, however, include considerable variability from decade to decade. For example, in the early part of the record (1920s to early 1940s), temperatures were moderate statewide, with annual averages generally near the long-term average, but were lower from about 1945 to about 1976 and then increased rapidly in the 1970s and 1980s and again in the mid-2010s (Figure 26.1). These variations are in part consistent with variations in large-scale patterns of climate variability in the Pacific Ocean;[40] in particular, Arctic warming in the early 20th century was intensified by Pacific variability (warm and cold anomalies of the Pacific sea surface temperatures).[41] Precipitation changes have

Observed and Projected Changes in Annual Average Temperature

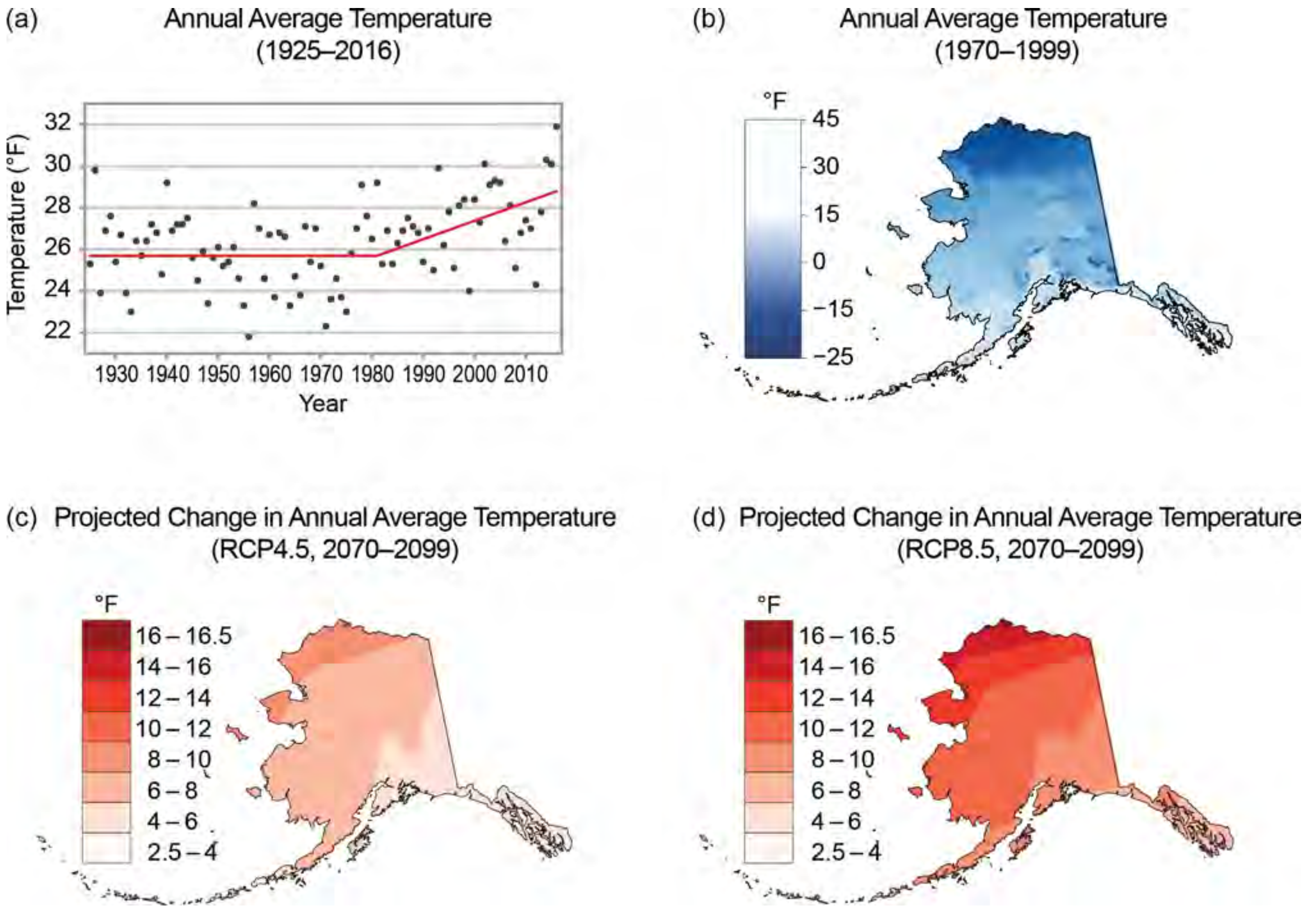


Figure 26.1: (a) The graph shows Alaska statewide annual average temperatures for 1925–2016. The record shows no clear change from 1925 to 1976 due to high variability, but from 1976–2016 a clear trend of +0.7°F per decade is evident. (b) The map shows 1970–1999 annual average temperature. Alaska has a diverse climate, much warmer in the southeast and southwest than on the North Slope (c) The map shows projected changes from climate models in annual average temperature for end of the 21st century (compared to the 1970–1999 average) under a lower scenario (RCP4.5). (d) The map is the same as (c) but for a higher scenario (RCP8.5). Sources: (a) National Oceanic and Atmospheric Administration and U.S. Geological Survey, (b–d) U.S. Geological Survey.

varied significantly across the state from 1920 to 2012, with long-term trends generally showing no clear pattern of change.[39]

Projected Temperature and Precipitation Changes

Recent availability of more localized climate information allows for more complete descriptions of the geographical variation in historical trends and climate projections.[39,42,43] Using downscaled global climate models[43] and the higher scenario (RCP8.5) (see Ch. 2: Climate, Box 2.7 and the Scenario Products section of App. 3),[44] more warming is projected in the Arctic and interior areas than in the southern areas of Alaska, and average annual precipitation increases are projected for all areas of the state, with greater increases in the Arctic and interior and the largest increases in the northeastern interior.

Climatic extremes are expected to change with the changing climate. Under a higher scenario (RCP8.5), by mid-century (2046–2065) the highest daily maximum temperature (the hottest temperature one might expect on a given summer day) is projected to increase 4°–8°F compared to the average for 1981–2000. For the same future period (2046–2065), the lowest daily maximum temperature (the highest temperature of the coldest day of the year) throughout most of the state is projected to increase by more than 10°F, with smaller projected changes in the Aleutian Islands and southeastern Alaska. Additionally, the lowest daily minimum temperatures (the coldest nights of the year) are projected to increase by more than 12°F. The number of nights below freezing would likely decrease by at least 20 nights per year statewide, and by greater than 45 nights annually in coastal areas of the North Slope, Seward Peninsula, Yukon–Kuskokwim Delta, Alaska Peninsula, and Southcentral Alaska.[45] Annual maximum one-day precipitation is projected to increase by 5%–10% in southeastern Alaska and by more than 15% in the rest of the state, although the longest dry and wet spells are not expected to change over most of the state.[45] Growing season length (the time between last and first frosts in a given year) is expected to increase by at least 20 days and perhaps more than 40 days compared to the 1982–2010 average.[35] Whether or not this increased growing potential is realized will largely depend on soil conditions and precipitation.

Key Message 1

Marine Ecosystems

Alaska's marine fish and wildlife habitats, species distributions, and food webs, all of which are important to Alaska's residents, are increasingly affected by retreating and thinning arctic summer sea ice, increasing temperatures, and ocean acidification. Continued warming will accelerate related ecosystem alterations in ways that are difficult to predict, making adaptation more challenging.

Arctic sea ice—its presence or absence and year-to-year changes in extent, duration, and thickness—in conjunction with increasing ocean temperatures and ocean acidification, affects a number of marine ecosystems and their inhabitants, including marine mammals, the distribution of marine Alaska fish and their food sources.[37]

Arctic Sea Ice Continues to Change

Since the early 1980s, annual average arctic sea ice extent has decreased between 3.5% and 4.1% per decade, and September sea ice extent, which is the annual minimum extent, has decreased between 10.7% and 15.9% per decade. As the climate continues to warm, it is likely that there will be a sea ice-free Arctic during the summer within this century.[37,46]

Sea ice provides an important surface for algal production and growth in marine ecosystems during spring. This production beneath the sea ice is an important source of carbon for pelagic (mid- to upper-water column) grazers, such as copepods and krill, and for benthic (lower-water) detritivores, such as clams and worms that feed on dead, organic material.[47,48] In turn, the abundance of these animals provides food for higher trophic-level organisms such as fish, birds, and mammals in regional marine ecosystems. The presence or absence of sea ice affects the transfer of heat, water temperature, and nutrient transport, as well as other processes (such as the breakdown or transformation of organic matter into its simplest inorganic forms) that affect ecosystem productivity.[49] In the Arctic, higher-level organisms such as Arctic cod,[17] polar bears, and walruses[50,51,52,53] are dependent upon sea ice for foraging, reproduction, and resting and are directly affected by sea ice loss and thinning (Box 26.1).

Box 26.1: Polar Bears and Walruses

Polar bears and walruses are both dependent on sea ice during parts of their lives. Polar bears rely on sea ice to access prey and establish maternal dens, and Pacific walruses rely on drifting sea ice as a platform to rest on between foraging dives. Changes in the distribution of seasonal sea ice have resulted in changes in the behavior, migration, distribution, and, in some areas, population dynamics of both species. Changes in spring ice melt have affected the ability of Alaska coastal communities to meet their walrus harvest needs, resulting in low harvest levels in several recent years. Ongoing research seeks to forecast the population-level consequences of sea ice changes for polar bears and walruses by studying the animals' behavior changes, especially in response to increased shipping and changes in subsistence harvest practices. Changes in the ability of Indigenous communities to access these two species in the future may be harder to assess, but that access will be crucial for the short- and long-term hunting success and resultant well-being of the communities.

Figure 26.2: (a) An adult female polar bear and cub are shown near Kaktovik, Alaska, in September 2015. (b) Walruses gathered on the shores of the Chukchi Sea near Point Lay, Alaska, in September 2013. Photo credits: (a) Stewart Breck, USDA (b) Ryan Kingsbery, USGS.

Ocean Acidification

The oceans are becoming more acidic (known as ocean acidification) in an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions (Ch. 9: Oceans, KM 1 and 2). Ocean acidification negatively affects organisms such as corals, crustaceans, crabs, mollusks, and other calcium carbonate-dependent organisms such as pteropods (free-swimming pelagic sea snails and sea slugs), the latter being an important part of the food web in Alaska waters. Some studies in the nutrient-rich regions have found that food supply may play a role in determining the resistance of some organisms to ocean acidification.[54]

Changes in ocean chemistry and increased corrosiveness are exacerbated by sea ice melt, respiration of organic matter, upwelling, and glacial runoff and riverine inputs, thus making the high-latitude North Pacific and the western Arctic Ocean (and especially the continental shelves of the Bering, Chukchi, and Beaufort Seas; see Figure 26.3) particularly vulnerable to the effects of ocean acidification. Also, more ice-free water will indirectly allow for greater uptake of atmospheric CO_2.[18,55,56] More recent research suggests that corrosive conditions have been expanding deeper into the Arctic Basin over the last several decades.[57] The annual average aragonite saturation state (a metric used to assess ocean acidification) for the Beaufort Sea surface waters likely crossed the saturation horizon near 2001),[18] meaning that the Beaufort Sea is undersaturated (lacking sufficient concentrations of aragonite) most of the year—a condition that limits the ability of many marine species to form shells or skeletons (Figure 26.3). Under the higher scenario (RCP8.5), the Chukchi Sea is projected to first cross this threshold around 2030 and then remain under the threshold after the early 2040s, and the Bering Sea will likely cross and remain under the threshold around 2065 (Figure 26.3).[18]

Through lab experiments, ocean acidification has been shown to affect the growth, survival, sensory abilities, and behavior of some species, especially species of importance to Alaska, such as Tanner and red king crab and pink salmon.[58,59,60,61,62] Studies indicate flatfish, such as the northern rock sole, are sensitive to lowered pH (lower pH equates to higher acidity), while walleye pollock have not shown adverse effects on growth or survival.[63,64] Pteropods play a critically important role in the Alaska water food web and have been shown to be particularly susceptible to ocean acidification. The effect of ocean acidification on pteropods manifests itself as severe shell dissolution, impaired growth, and also reduced survival.[65,66] More importantly, these effects are observed in the natural environment, making pteropods one of the most susceptible indicators for ocean acidification.[65,67,68] The effects observed in pteropods can be interpreted as the early-warning signal of the impacts of ocean acidification on the ecosystem integrity, linking pteropod effects to higher trophic levels, in particular fish (such as pink salmon, sole, and herring) that are feeding on pteropods. However, the impacts on these food webs are highly uncertain[69,70,71] but can be more detrimental in the high-latitudinal ecosystems with fewer species and shorter food chains.[67,68]

Projected Changes in Arctic Ocean Acidity

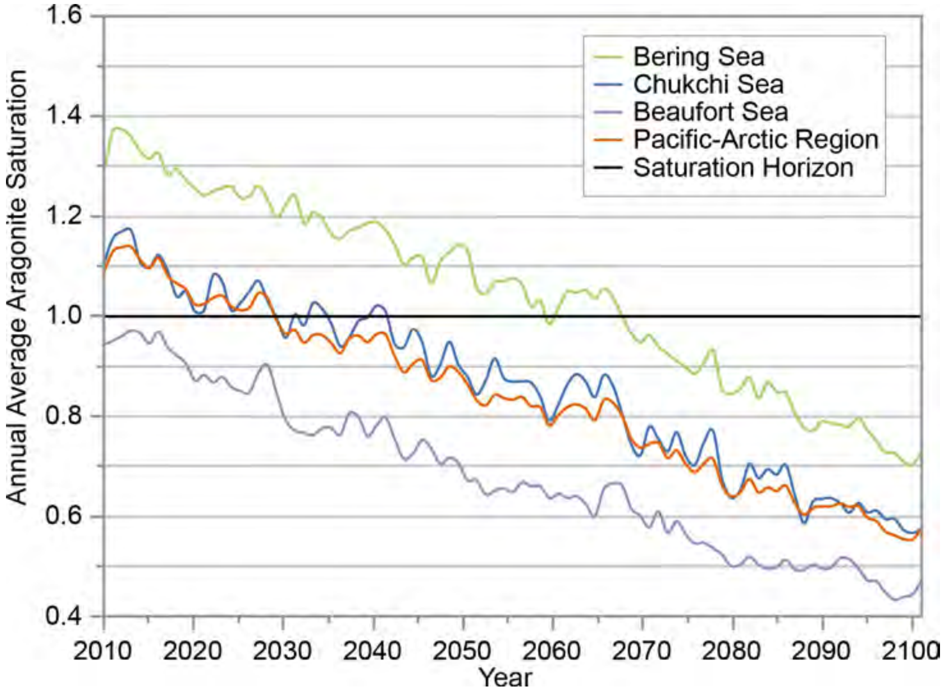


Figure 26.3: The time series shows the projected decline in the annual average aragonite saturation (one of the consequences of increased ocean acidity, or lower pH) for the Bering Sea, Chukchi Sea, Beaufort Sea, and for the entire Pacific-Arctic region under the higher scenario (RCP8.5). Aragonite saturation is a metric used to assess ocean acidification and the ability for organisms to build shells and skeletons. The annual average saturation state for the Beaufort Sea surface waters likely crossed the saturation horizon—a tipping point—around 2001, meaning it is currently undersaturated and its marine ecosystems are vulnerable to the impacts of ocean acidification during most of the year. The Chukchi Sea is projected to first cross this threshold around 2030 and then likely remain under the threshold after the early 2040s; the Bering Sea is projected to be a concern after 2065. Source: adapted from Mathis et al. 2015.[18]

Alaska Fishes

More than 600 fish species have been found in Alaska waters,[72] and Alaska's industrial fisheries in the Gulf of Alaska and Bering Sea are among the most productive and valuable in the world, with an estimated average of $5.9 billion of total economic activity in 2013–2014 (in 2013–2014 dollars).[73,74] Climate effects on Alaska's marine ecosystems are of considerable economic interest because of their impacts on the commercial harvests from the Northeast Pacific and subsistence fisheries for salmon, char, whitefishes, and ciscos in the Arctic and on these species or others elsewhere in the state.

The distribution of many ocean fish species is shifting northward as the ranges of warmer-water species expand and colder-water species contract in response to rising ocean temperatures (Ch. 9: Oceans, KM 2), with the confirmed presence of 20 new species and 59 range changes in the last 15 years in the Chukchi and Beaufort Seas.[17] In the Bering Sea, Alaska pollock, snow crab, and Pacific halibut have generally shifted away from the coast and farther from shore since the early 1980s.[75] These changes reflect possible northward shifts in species distributions, particularly in the Bering Strait region.[76]

Marine ecosystem food webs are also being affected by climate change. Changes in sea ice cover and transport of warmer seawater and drifting organisms (such as plankton, bacteria, and marine algae) may be impacting how surface ocean waters interact with the bottom ocean waters, especially over the shallow northern Bering and Chukchi Sea

Changes to North Pacific Marine Ecosystems in a Warming Climate

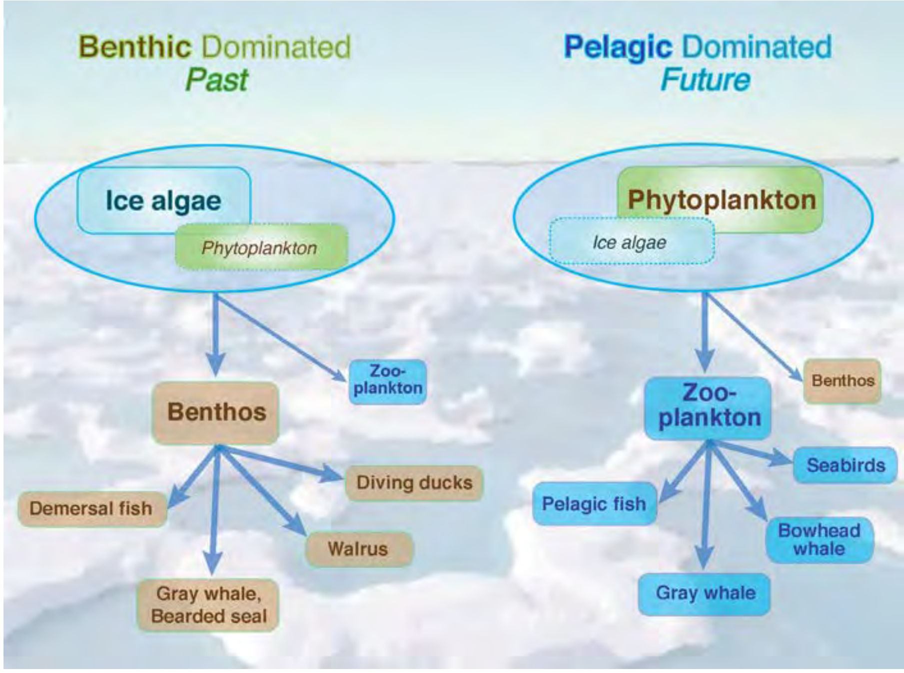


Figure 26.4: As sea ice thins and retreats earlier in the season, it is anticipated that food webs under the ice will switch from a benthic-dominated (lower in the water to seafloor) to a pelagic-dominated (middle to higher in the water) marine ecosystem. Source: Moore and Stabeno 2015.[78]

shelves. As relatively larger organisms (such as zooplankton, which are very tiny marine animals in the water column) become more abundant, they are able to efficiently graze on the smaller plant organisms (such as phytoplankton—microscopic marine plants) and reduce the amount of food supplied to the bottom sediments. This in turn can impact benthic animals that are important prey to marine mammals, such as walrus, gray whales, and bearded seals.[77,78,79] A switch from benthic (lower) to pelagic (upper) marine ecosystem activities that link organisms and their environment, in combination with warmer temperatures, may result in this northern shelf region changing from a benthic-dominated to a pelagic-dominated marine ecosystem (Figure 26.4) and becoming a hotspot of invasion, expansion, and increased abundance of fish species such as pollock and Pacific salmon.[79] The changing conditions confer physiological and competitive benefits to species favoring warmer water conditions, such as saffron cod, and potential negative impacts to Arctic cod populations, a keystone species in Chukchi and Beaufort Seas food webs.[17]

Changes in climate-related events are likely to affect management actions and economic drivers, including fisheries, in complex ways.[80] An example is the recent heat wave in the Gulf of Alaska, which led to an inability of the fishery to harvest the Pacific cod quota in 2016 and 2017 and to an approximately 80% reduction in the allowable quota in 2018.[81] These reductions are having significant impacts on Alaska fishing communities and led the governor of Alaska to ask the Federal Government to declare a fisheries disaster. Events such as these are requiring the use of multiple, alternative models to appropriately characterize uncertainty in future population trends and fishery harvests.[82] The need to address uncertainty is especially true for the Eastern Bering Sea pollock fishery, which is one of the largest in the United States.[83] While most scientists agree that walleye pollock populations in the eastern Bering Sea are likely to decrease in a warming climate,[84,85,86,87,88] these effects can be mitigated to some extent by adopting alternative fish harvest strategies,[89] and economic losses may be partially offset by increased pollock prices.[90]

Key Message 2

Terrestrial Processes

Alaska residents, communities, and their infrastructure continue to be affected by permafrost thaw, coastal and river erosion, increasing wildfire, and glacier melt. These changes are expected to continue into the future with increasing temperatures, which would directly impact how and where many Alaskans will live.

As temperatures increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost (soil at or below the freezing point of water [32°F] for two or more years) is expected to continue, with associated impacts to infrastructure,[91] river and stream discharge,[92] water quality,[93,94] and fish and wildlife habitat. Wildfires and temperature increases have caused changes in forest types from coniferous to deciduous in interior Alaska, and these changes are projected to continue with increased future warming and fire.[95,96] In tundra ecosystems, temperature increases have allowed an increase of shrub-dominated lands.[97,98] With the late-summer sea ice edge located farther north than it used to be, storms produce larger waves and cause more coastal erosion.[19] In addition, ice that does form is very thin and easily broken up, giving waves more access to the coastline.[99] A significant increase in the number of coastal erosion events has been observed as the protective sea ice embankment is no longer present during the fall months.[100] In addition, glaciers continue to diminish, and associated runoff influences other terrestrial ecosystems.[101]

Permafrost

About half of Alaska is underlain by permafrost—an essential geographic quality that affects landscape patterns and processes,[102] and construction in the Arctic depends on the ability of permafrost to remain frozen. Since the 1970s, Arctic and boreal regions in Alaska have experienced rapid rates of warming and thawing of permafrost,[103,104,105,106] with spatial modeling[107] projecting that near-surface permafrost will likely disappear on 16% to 24% of the landscape by the end of the 21st century.[108] Confidence in these estimates is higher than for those in the Third National Climate Assessment[109] due to more field sample sites, higher resolution imagery for mapping, and advanced geographic modeling techniques.

Permafrost degradation impacts society in both tangible and intangible ways. Physical impacts of thawing permafrost include unsafe food storage and preservation (Box 26.2), decreased bearing capacities of building and pipeline foundations, damage to road surfaces, deterioration of reservoirs and impoundments that rely on permafrost for wastewater containment, reduced operation of ice and snow roads in winter, and damage to linear infrastructure (such as roads and power lines) from landslides.[20] As permafrost thaws, the ground sinks (known as subsidence), causing damage to buildings, roads, and other infrastructure;[110,111,112] these impacts to structures and facilities are likely to increase in the future.[91] In addition to physical impacts, thawing permafrost has important societal impacts that cannot be quantified. The loss of cultural heritage for Alaska's Indigenous people includes the loss of archaeological sites, structures, and objects, as well as traditional cultural properties, which affects their ability to connect to their ancestors and their past.[113]

Box 26.2: Iñupiat Work to Preserve Food and Traditions on Alaska's North Slope

Local traditional foods are important for nutritional, spiritual, cultural, and social benefits. Many of these foods are sometimes stored in traditional underground ice cellars kept cold by the surrounding permafrost. With warming climate conditions, many of these ice cellars are beginning to thaw, increasing the risks for foodborne illness, food spoilage, and even injury from structural failure. The Iñupiat community of Nuiqsut, located on Alaska's North Slope, is among the communities using new technology to improve the storage environment in existing cellars. Find out more at https://toolkit.climate.gov/case-studies/i%C3%B1upiaq-work-preserve-food-and-traditions-alaskas-north-slope.

Wildfire

The annual area burned by wildfires in Alaska varies greatly year-to-year, but the frequency of big fire years (larger than 2 million acres) has been increasing—with three out of the top four fire years (in terms of acres burned) in Alaska occurring since the year 2000.[114] As a result, the vegetation of forested Interior Alaska now has less acreage of older spruce forest and more of post-fire early successional vegetation, birch, and aspen than it did prior to 1990.[95] This change favors shrub-adapted wildlife species such as moose but also destroys the slow-growing lichens and associated high-quality winter range that caribou prefer, though the effects of fire-driven habitat changes to caribou population dynamics are uncertain.[23] Some rural communities, however, have adapted to these vegetation changes by designing small-scale programs that enhance moose browsing (feeding on leaves, twigs, or tree branches) or developing biofuel infrastructure integrated with fire prevention tactics.[115,116] In addition to range expansion due to changes in wildfire, shrubs have been increasing in density and height in tundra environments due to increasing temperatures,[98] with shrub expansion in tundra ecosystems being observed across the North American Arctic.[117,118] Shrub-adapted wildlife species such as moose and snowshoe hares, and in some cases beaver, have followed the expansion of shrubs and are now common in parts of Arctic Alaska and Canada, where they were previously rare or absent.[24,119,120] The area burned by wildfires may increase further under a warming climate.[25] Projections of burned area for 2006–2100 are estimated at 98 million acres under a lower scenario (RCP4.5) and 120 million acres under a higher scenario (RCP8.5).

Coastal and River Erosion

Flooding and erosion of coastal and river areas affect over 87% of the Alaska Native communities,[121,122,123,124,125] with some coastal areas being threatened due to changes in sea ice and increased storm intensity as a result of climate change.[122,126] Offshore and landfast sea ice is forming later in the season, which allows coastal storm waves to build while leaving beaches unprotected from wave action.[99,126,127,128,129] Rates of erosion vary throughout the state, with the highest rates measured on the Arctic coastline at more than 59 feet per year (Figure 26.5).[19] For context, one study noted that rates of coastal erosion may have varied from location to location but could have been more than 100 feet per year at the Canning River between Camden Bay and Prudhoe Bay.[130] Other researchers have come up with different rates along the Alaska Arctic coast.[19] Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to worsen flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat and cultural resources and requiring entire communities, such as Kivalina in northwestern Alaska (Ch. 1: Overview, Figure 1.18),[131] to relocate to safer terrain.[19,122,123]

Erosion Rates Along Alaska's North Coast

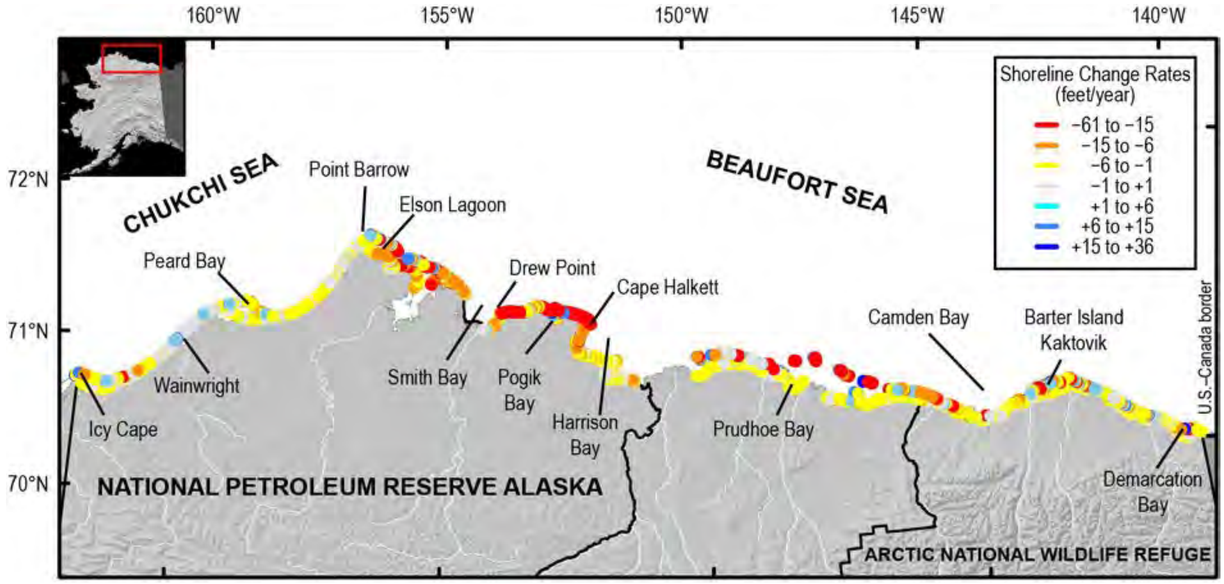


Figure 26.5: The map is of the north coast of Alaska and shows color-coded shoreline erosion rates, which can lead to the loss of habitat, cultural resources, and infrastructure. Source: adapted from Gibbs and Richmond 2015.[19]

Many Alaska communities that are not located on the coast are adjacent to large rivers, where riverine erosion is a serious problem,[123] with some communities (for example, Minto in 1969 and Eagle in 2009) having to relocate housing and other infrastructure due to erosion and associated flooding. Erosion rates vary, but conservative rates for the Ninglick River at Newtok range from 36 feet per year (west/downstream) to 83 feet per year (east/upstream), although actual observations by Newtok residents indicate a potential rate as high as 110 feet per year.[132] This has required the residents of Newtok to move to the new site of Mertarvik, about 9 miles away.[133]

In both coastal and river communities, various types of infrastructure and cultural resources are being threatened. A number of adaptation measures are being pursued or proposed[134,135] that include relocation, the construction of rock walls, the use of sandbags, and the placement of various forms of riprap, which may only slow or displace the erosion process and in some cases be maladaptive.[100,123]

Glacier Change

Glaciers continue to melt in Alaska, with an estimated loss of 75 ± 11 gigatons (Gt) of ice volume per year from 1994 to 2013,[136,137] 70% of which is coming from land-terminating glaciers; this rate is nearly double the 1962–2006 rate.[138] Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,[139,140,141,142] with the potential to alter streamflow along the Gulf of Alaska[143] and to change Gulf of Alaska nearshore food webs.[144]

Melting glaciers are likely to produce uncertainties for hydrologic power generation,[22] which is an important resource in Alaska.[145,146] In the short term, melting glaciers can increase hydropower capacity by increasing downstream flow; however, with continued melting there will likely be less meltwater for the future. This may be offset by an increase in precipitation in Alaska,[45] although an increase in precipitation does not necessarily lead to increases in catchment runoff (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM5).[147]

Key Message 3

Human Health

A warming climate brings a wide range of human health threats to Alaskans, including increased injuries, smoke inhalation, damage to vital water and sanitation systems, decreased food and water security, and new infectious diseases. The threats are greatest for rural residents, especially those who face increased risk of storm damage and flooding, loss of vital food sources, disrupted traditional practices, or relocation. Implementing adaptation strategies would reduce the physical, social, and psychological harm likely to occur under a warming climate.

The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States.

Direct Exposures

In general, even with a warming climate, Alaska is not expected to experience the extremes of heat and humidity found at lower latitudes; however, rising temperatures do pose a risk. Air conditioning in homes is rare in Alaska, so relief is seldom available for at-risk persons to escape high temperatures or from smoke exposure due to wildfires, assuming proper filters are not installed.

Winter travel has long been a key feature of subsistence food gathering activities for rural Alaska communities. Higher winter temperatures and shorter durations of ice seasons may delay or disrupt usual patterns of ice formation on rivers, lakes, and the ocean. For hunters and other travelers, this increases the risk of falling through the ice, having unplanned trip extensions, or attempting dangerous routes, leading to exposure injury, deaths, or drowning (Box 26.3).[26,148] Community search and rescue workers experience similar risks in searching for missing travelers, extending the threat across communities. Adaptation strategies being promoted include improved communication about local ice and water conditions, increasing use of survival suits and personal floatation devices,[149] and the use of personal locator beacons and messaging devices that can alert responders to a traveler at risk or provide reassurance and avoid unneeded search and rescue operations in high-risk conditions.[150]

Extreme weather events such as major storms, floods, and heavy rain events have all occurred in Alaska with resulting threats to human health.[153,154] For coastal areas, the damage from late-fall or winter storms is likely to be compounded by a lack of sea ice cover, high tides, and rising sea levels, which can increase structural damage to tank farms, homes, and buildings and can threaten loss of life from flooding. Such events can damage vital water and sanitation systems in several ways, including saltwater intrusion of drinking water sources, loss of power leading to freezing and damage to water and sewer systems, or disruptions to community septic drain fields and water distribution systems. These events would all reduce access to water/sewer services, leading to an increased risk of water-related infectious diseases.[155] Similar events threaten communities on rivers, where flooding due to increased glacial melt or heavy rains can cause extensive structural damage and loss of life. It is uncertain if climate warming will increase severe mid-winter ice jam events or reduce their hazards due to more gradual melting of ice with earlier spring thaws.[156] Improved real-time observations and river breakup forecasts are now available for use by decision-makers to help prepare in advance of

Box 26.3: Climate Change and Public Health

Environmental changes from a warming climate, such as unpredictable weather that greatly deviates from the norm, can significantly affect the physical and mental health of rural Alaskans. They may face difficulty harvesting local food and hazardous travel across the landscape. These climate-related challenges are being addressed by the Alaska Native Tribal Health Consortium Center for Climate and Health, which is working to recognize these new vulnerabilities and to support healthy adaptation strategies. Outcomes and activities from this effort include

- the One Health Group, which consists of federal, state, and nongovernmental organizations, conducts quarterly webinars and presentations on the intersection between human, animal, and environmental health. Cosponsored by the Centers for Disease Control and Prevention, this forum improves communication and situational awareness about climate change and public health in Alaska;[151]

- the Local Environmental Observer (LEO) Network,[6] a forum funded by the Environmental Protection Agency, the Department of the Interior, and the Bureau of Ocean Energy Management, is used for tracking local observations of environmental events and connecting communities with technical resources using an internet-based mapping tool and smartphone applications;

- comprehensive climate vulnerability assessments of rural Alaska communities;[152] and

- an electronic newsletter, *Northern Climate Observer*, which provides weekly access to articles and observations about the circumpolar north.[152]

More can be learned about these Alaska health-related resources at: https://toolkit.climate.gov/case-studies/addressing-links-between-climate-and-public-health-alaska-native-villages

potential flood events; such systems could help communities reduce the negative effects of seasonal flooding.[157]

Climate-driven increases in air pollution in Alaska are primarily linked to the increases in wildfire frequency and intensity. Wildfires, however, threaten individual safety in adjacent communities and pose risks downwind from smoke inhalation, particularly for children and persons with chronic respiratory and cardiovascular conditions (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1).[10,158] Adaptations to protect persons at risk from wildfire exposure include using community air quality indices linked to recommendations for specific groups, educating people about outdoor activities and use of masks, and creating a “clean room” using high-efficiency particulate air (HEPA) dust filters or air conditioning.[159] It is also likely that there will be an increased risk of respiratory allergies related to longer and more intense seasonal pollen blooms and mold counts (Ch. 13: Air Quality, KM 3).[160] Public reporting of pollen counts conducted in Anchorage and Fairbanks[161] is used to advise allergy sufferers of increasing risks and is linked to recommendations to avoid exposure and reduce symptoms. Increased respiratory symptoms have also been reported in communities that are experiencing increased windblown dust. Adaptations include dust suppression, improving indoor air quality, and use of masks.

Indirect Effects

Climate change has indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting the range and concentration of disease-spreading animals and food security, especially in rural communities (Ch. 14: Human Health, KM 1). These changes can result in positive and negative health effects; many are site specific, and documentation is highly dependent on availability of monitoring or reporting data.

In-home water and sanitation services are a fundamental contributor to health, and the absence of such services in 15% of rural Alaska homes is associated with increased risk of gastrointestinal, respiratory, and skin infections.[155,162,163] Climate-related environmental changes that can affect access to water and sanitation services have been well-documented.[154] These changes include loss of surface water through drainage of tundra ponds, lower source-water quality through increased riverbank erosion due to permafrost thaw or saltwater intrusion in coastal communities, and increased coastal erosion or storm surge leading to wastewater treatment system damage.[164] Permafrost thawing poses a threat to centralized water and wastewater distribution systems that need stable foundations to maintain system integrity. More flexible service connections have been used to reduce damage from movement caused by permafrost thawing.[165] People cope with water shortages by use of rainwater catchment or other untreated water sources, reuse of water used for clothes or personal hygiene, or rationing of water to prioritize drinking and cooking. Such practices, however, could lead to increased risk of waterborne infectious diseases or increased spread of person-to-person infections through decreased hygiene. Increased silt or organic material in source water can quickly clog filters, increasing costs of water treatment. This can result in reduced filtration effectiveness and increased exposure to waterborne pathogens, such as *Giardia intestinalis*.[165] The state of Alaska is funding development and testing of decentralized water and sanitation systems that use in-home treatment, water reuse, and other efficiencies that may be an alternative in homes without existing services or if centralized systems fail.[166]

Changes in insect and arthropod ranges due to climate change have raised human health concerns, such as the documented increase in venomous insect stings in Alaska.[167,168] Tick-borne human illnesses are uncommon in Alaska, but new reports of ticks on domestic dogs without travel exposure outside Alaska raise concerns about tick range extension into Alaska and the potential for introduction of new pathogens.[169] Several human infectious diseases could potentially expand in a changing Alaska climate. For example, climate change may allow some parasites to survive longer periods, provide an increase in the annual reproduction cycles of some disease-carrying insects and pests (vectors), or allow infected host animal species to survive winters in larger numbers, all increasing the opportunity for transmission of infection to humans.[170] However, some of these diseases are rare, and detecting increases is hampered by Alaska's small population, limited access to diagnostic testing, and the absence of surveillance for some human illness (for example, toxoplasmosis, an infection caused by a parasite). Foodborne pathogens, including parasites, have been identified as likely to increase due to increased temperature changes and increasing exposure.[171,172] In Alaska, disruption of ice cellars from thawing permafrost and coastal erosion has raised concerns about food spoilage or infectious outbreaks, but documented human illness events are lacking. Likewise, the documented northward range expansion of beavers has been postulated to increase the threat of waterborne *Giardia* infections in humans; however, human *Giardia* illness reports have been stable in Alaska and show no increasing regional trends.[173] Emerging infectious threats led to the formation of an Alaska One Health Group, which meets quarterly to combine perspectives from human, animal, and environmental health and uses new data generated from the Local Environmental Observer (LEO) Network.[6,174] A new rural monitoring program has been developed for tribal community settings to include collection of data on infectious threats from food, animals, and water.[175]

Harmful algal blooms (HABs) produce toxins that can harm wildlife and pose a health risk to humans through consumption of contaminated shellfish. Because phytoplankton growth is increased in part by higher water temperatures, risks for HAB-related illnesses, including paralytic shellfish poisoning (PSP), may increase with climate change. PSP is a long-recognized, untreatable, and potentially fatal illness caused by a potent neurotoxin in shellfish. PSP illnesses are considered a public health emergency. Two approaches are being used to reduce PSP in Alaska. First, because recreational shellfish harvesting is very popular in Alaska (see Ch. 24: Northwest, KM 2 and 4 and Figure 24.7), some communities have begun to monitor for PSP toxins among shellfish at locations used for noncommercial harvests using a "catch, hold, and test" approach, which, if coupled with reliable testing methods, could provide a strategy to reduce risk and maintain these important local harvests.[176] The second adaptation approach uses local water temperature data to predict the risk of HAB growth in Kachemak Bay. The effectiveness of these methods for reducing human health risk has not been established.[7]

An example of climate-associated disease emergence and response is the 2004 outbreak of acute gastroenteritis that was associated with consumption of raw farmed oysters contaminated by the bacterium *Vibrio parahaemolyticus*. This is a well-recognized threat in warmer coastal waters of North America but was previously unreported in Alaska. However, in 2004, surface water temperatures above shellfish beds had warmed enough to support *V. parahaemolyticus* growth. This warming was part of a documented long-term warming trend, and the outbreak is indicative of a northward range extension of this pathogen by about 600 miles.[177] In response to the outbreak, the State of Alaska developed a control plan that includes water temperature monitoring around commercial oyster beds and uses threshold-based responses to reduce health risks from this pathogen.[176] Fortunately, *V. parahaemolyticus* contamination has not become a major health threat. Alaska has averaged only three reported cases per year since the first outbreak, and many of these are traceable to non-Alaska shellfish; however, the projected rise in sea surface temperatures in Alaska will favor increased *Vibrio* growth and seasonal range expansion with an increased risk of human exposure and illness.[178,179]

Psychological and Social Effects

Climate change is a common concern among Alaskans and is associated with feelings of depression and uncertainty about the potential changes to communities, subsistence foods, culture, and traditional knowledge and the potential of relocation from long-established traditional sites.[122] These uncertainties and threats have effects on mental health and on family and community relationships and may lead to unhealthy responses such as substance abuse and self-harm.[180] This is especially true of Indigenous peoples, who have a deep connection to their home areas, often described as sense of place.[181,182,183,184] Over generations, Indigenous communities have developed extensive knowledge about their areas and the plants and animals with which they share an ecosystem.[185] As the effects of climate change are felt in the landscape, many Alaska Natives feel a sense of personal loss as the familiar has become unpredictable and sometimes strange.[125] This uncertainty has also reduced traditional camping activities that strengthen community ties. Damage or loss to cultural sites and properties is also a great concern, reducing the sense of cultural continuity in one's place along with information about living and adapting there. In the context of many other social, technological, economic, and cultural changes affecting Indigenous communities, the continuation of traditional activities in traditional places can be a bedrock of stability. When this, too, is threatened, a wider sense of environmental security is at risk.[125] Community relocation or the movement of persons away from climate-threatened areas can have intergenerational effects through loss of cultural connections and adverse childhood experiences leading to poorer health outcomes. The Alaskans most vulnerable to these climate-related changes are those who are most dependent on subsistence foods, the poor, the very young, the elderly, and those with existing health conditions that require ongoing care, that limit mobility, or that reduce capacity to accommodate changes in diet, family support, or stress.[11]

Key Message 4

Indigenous Peoples

The subsistence activities, culture, health, and infrastructure of Alaska's Indigenous peoples and communities are subject to a variety of impacts, many of which are expected to increase in the future. Flexible, community-driven adaptation strategies would lessen these impacts by ensuring that climate risks are considered in the full context of the existing sociocultural systems.

Alaska's climate is changing rapidly, with far-reaching effects throughout the state, including in its Indigenous communities. Alaska's rural communities are predominantly inhabited by Indigenous peoples, with some of them disproportionately vulnerable to socioeconomic and environmental change; however, they also have rich cultural traditions of resilience and adaptation.[109,125,134,186,187,188] The impacts of climate change are likely to affect all aspects of Alaska Native societies, from nutrition, infrastructure (see Key Message 2), economics, and health consequences to language, education, and the communities themselves. Most of these impacts are also experienced in other rural, predominantly nonnative communities in Alaska and are therefore covered in other sections of this chapter.

Subsistence Activities

Subsistence hunting, fishing, and gathering provide hundreds of pounds of food per person per year in many Alaska Native villages.[189,190] Producing, preparing, sharing, and consuming these foods provide a wealth of nutritional, spiritual, cultural, social, and economic benefits. Traditional foods are widely shared within and between communities and are a way of strengthening social ties.[191,192,193] Climate change is altering the physical setting in which these subsistence activities are conducted.[15,182] Examples include

- reducing the presence of shore-fast ice used as a platform to hunt seals[194] or butcher whales,[195]
- reducing the availability of suitable ice conditions for hunting seals and walrus (Figure 26.6),[28] and
- exacerbating the risks of winter travel due to increasing areas of thin ice and large fractures within the sea ice (commonly referred to as "leads") as well as water on rivers.[26,27,196]

However, climate change is also providing more opportunity to hunt from boats late in the fall season or earlier in spring.[125] Increasing temperatures affect animal distribution and can alter the availability of subsistence resources, often making hunting and fishing harder but sometimes providing new opportunities, such as fall whaling on St. Lawrence Island.[197] Shellfish populations, an important subsistence and commercial resource along the Alaska coast, have been declining for more than 20 years throughout coastal Alaska, with ocean warming and ocean acidification (Ch. 9: Oceans) contributing to the decline (see Key Message 1). Warm temperatures and increased humidity are also affecting ice cellars used traditionally to store food (as noted earlier in this chapter), thereby making it harder to air-dry meat and fish on outdoor racks, causing food contamination.[131,198] Some communities have found new storage methods or have changed to an increasingly Western diet. Subsistence foods decrease the costs of feeding a family compared to purchased foods, which in rural Alaska are almost twice the cost of those in Anchorage.[199,200] One net result of all these changes is an overall decrease in food security for residents of rural Alaska Native communities (Ch. 10: Ag & Rural, KM 4).[29]

Thawing permafrost in the boreal forest has accelerated land and riverbank erosion (see Key Message 2). Subsistence harvesters have expressed concern that less precipitation is resulting in rivers becoming shallower and lakes drying.[15] The increasingly dynamic nature of interior river characteristics has contributed to more challenging boat navigability and less dependable locations for fish wheel and net sets. These climate-induced environmental changes also occur in the context of other regulatory, social, administrative, legal, and economic constraints, which affect the ways that climate change impacts manifest themselves in specific locations.[201] As the environment changes, overall well-being can

Variable Weather Affects Harvest Levels

Figure 26.6: These images of marine mammal meat drying on racks in Gambell, Alaska, in (a) June 2012 and (b) July 2013 illustrate the interannual variability of harvests due to sea ice and weather conditions and suggest what the future may hold if ice and weather trends continue. Photo credit: Henry P. Huntington.

also suffer from the sense of dislocation and from losing the spiritual and cultural benefits of providing and sharing traditional foods, as these activities do much to tie communities together.[202,203,204]

Adaptation Actions

In the midst of negative impacts from climate change, Alaska Native communities display remarkable capacity for response and adaptation (Ch. 15: Tribes, KM 3).[29,125,205] Sometimes, adaptation means expanding networks for sharing of foods and ideas, as has been seen in the Kuskokwim River area;[206] applying Indigenous evidence and approaches to habitat protection;[27] or giving communities more say in identifying priorities for action and directing available funds for community needs and action-oriented science.[125] A clear example is the community of Shaktoolik's initiative to build a community-driven, mile-long and seven-foot-high berm made out of driftwood and gravel to protect itself from flooding and erosion during storm episodes.[207] As storms increase in frequency and intensity,[126] some builders in Gambell, Alaska, are considering efficient house designs that avoid exposure to prevailing winds and piling up of snow at the doors.[208,209] While some of these initiatives are part of statewide efforts to address common threats from climate change,[210] at other times communities have been able to take advantage of new opportunities, such as expanding networks for sharing of foods and ideas,[206] fishing for new species,[211] or applying Indigenous knowledge and frameworks to habitat protection and ecosystem management.[27] Further effort is warranted both on cataloging community response to climate-related changes in the environment and on enhancing the transfer of knowledge among rural communities on innovative and effective adaptations.[212]

Key Message 5

Economic Costs

Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska. It is also reducing heating costs throughout the state. These effects are very likely to grow with continued warming. Timely repair and maintenance of infrastructure can reduce the damages and avoid some of these added costs.

Climate change in Alaska has caused regionally disparate economic effects. The infrastructure and community relocation costs, along with potential adverse effects on fisheries, accrue predominantly to rural communities. While both urban and rural communities benefit from reduced space heating costs, the urban communities bear few of the costs and risks. The profound and diverse climate-driven changes in Alaska's physical environment and ecosystems generate economic impacts through their effects on environmental services. These services include positive benefits directly from ecosystems (for example, food, water, and other resources), as well as services provided directly from the physical environment (for example, temperature moderation, stable ground for supporting infrastructure, and smooth surface for overland transportation).[213] Some of these effects are relatively assured and in some cases are already occurring. Other impacts are highly uncertain, due to their dependence on the structure of global and regional economies and future human alterations to the environment[112] decades into the future, but they could be large.

Infrastructure

Threats to infrastructure in Alaska from coastal and riparian erosion caused by the combination of rising sea levels, thawing permafrost, reduced sea ice, and fall storms are well known.[214,215] A study published in 2008 projected that the cost (for 2008–2030) associated with early reconstruction and replacement of public infrastructure (roads, public buildings, airports, and rail lines) caused by damage from these threats was estimated to be between $3.6 and $6.1 billion (in 2008 dollars).[20] Assuming the 2.85% annual real interest rate used in these studies, the cost translates to an average of $250 to $420 million per year (in 2015 dollars). A more recent study estimated a somewhat smaller annual cost of $110–$270 million between 2015 and 2060 for maintenance and repair costs to mitigate or remediate damage to public infrastructure from climate warming (in 2015 dollars, discounted 3%) under the lower scenario (RCP4.5) and higher scenario (RCP8.5), respectively.[11,91] Projecting these costs to the end of the century, cumulative effects amounted to $3.7 billion under the lower scenario (RCP4.5) to $4.5 billion under the higher scenario (RCP8.5) for reactive repair and replacement, but $2.0 to $2.5 billion for proactive adaptation costs, depending on the climate change scenario[11] (in 2015 dollars, discounted 3%). The lower cost assumes that funding will be available for maintenance and repair before facilities require replacement, which is not guaranteed.[216,217] Both studies excluded losses to commercial and industrial buildings and private homes.

Coastal and riverine erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.[123] Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office study ranged from $80 to $200 million per community (dollar year not reported).[122,218] Beyond financial cost, additional challenges of relocation involve legal and policy obstacles, as well as deep cultural ties to landscape and place. Construction of rock walls, use of sandbags and riprap,[219] and replacement infrastructure for communities that are partially relocated[123] represent additional costs, as would loss of productivity and income from lack of access to utilities and drinking water and temporary displacement of residents when water and sewer lines rupture.[220,221,222]

Ice Road Transportation

In rural Alaska, where surface transportation infrastructure is extremely limited, snow and ice offer a low-cost alternative for moving people, goods, and heavy industrial equipment. As the climate warms, the resulting shorter and milder cold season reduces the season length for ice road use, increases the risk of travel on river ice, and increases the wear and tear on snow machines. Loss of overland winter transportation raises costs for extractive industries (such as oil extraction and logging) and rural Alaska households. A 2004 report estimated the cost of ice roads on the North Slope of Alaska at $100,000 per mile, versus as much as $2 million per mile for a gravel road (in 2003 dollars; $127,000 per mile for ice roads and $2.5 million for gravel in 2015 dollars).[223] Costs of foregone economic activity[103] and increased risk of winter travel are more difficult to quantify.[224]

Marine Vessel Traffic

Reduced seasonal ice has been associated with increased marine traffic in the U.S. maritime Arctic.[225] A longer ice-free shipping season could reduce the cost of shipping ore from the Red Dog mine and other mines in the region,[154,226] as well as increase certainty of shipping production facilities and equipment to North Slope oil fields. Adverse navigability effects of reduced river discharge[227] could offset beneficial effects of an extended ice-free shipping season on the cost of barge service to communities in western and northern Alaska.

Northward progression of the late-summer sea ice edge creates opportunities for increased vessel traffic of various types (including cargo and tanker ships, tour boats, and government vessels, including military)[226] to pass through the Bering Strait to or from the Northern Sea Route, the Northwest Passage,[228] and, by mid-century, directly across the Arctic Ocean.[229,230] As the Arctic Ocean opens, the Bering Strait will have increased strategic importance.[231] Lack of deep-water ports, vessel services, search and rescue operations, environmental response capabilities, and icebreaking capacity will impede expansion of vessel traffic.[225,226,230,232,233] Significant effects are likely several decades away, and new transarctic shipping will likely have little economic effects within Alaska in the near term but would bring environmental risks to fisheries and subsistence resources.[234] New oil and gas exploration and development in new areas within the U.S. economic zone are unlikely, as the Arctic Ocean waters that are not already accessible are generally off the U.S. continental shelf.

Wildfire Costs

Increasing incidence of wildfire near inhabited areas leads to a wide array of costs, including firefighting costs, health and safety impacts, property damage, insurance losses, and higher costs of fire insurance (Figure 26.7).[235] In addition, tourism businesses may experience short-term losses as visitors avoid recently burned areas. A recent estimate projected an increase in wildfire suppression costs of $25 million more per year (in 2015 dollars, 3% discount rate) under the lower scenario (RCP4.5) above the 2002–2013 annual average by the end of the century.[21] The cost could be higher if the footprint of human settlement expands and the geographic area designated for active fire suppression expands accordingly. Property damage from wildfires will likely increase as the number of large fire years increases. The Millers Reach Fire in 1996 destroyed 454 structures, including 200 homes in the Matanuska-Susitna Borough, with an estimated total cost of $80 million (in 1996 dollars; $120 million in 2015 dollars).[236] A subsequent fire in 2015 in the same general area destroyed another 55 homes and heavily damaged 44 other structures.[237]

Wildfire Destroys Homes Near Willow, Alaska

Figure 26.7: The 7,220-acre Sockeye Fire near Willow, Alaska, totally destroyed 55 residences and damaged 44 in mid-June 2015. Photo courtesy of Matanuska-Susitna Borough/Stefan Hinman.

Heating Costs

Increasing winter temperatures have reduced the demand for energy and associated costs to provide space heating for Alaska homes, businesses, and governments. Heating degree days (a measure of the energy required to heat homes and other buildings) have declined substantially in most parts of the state as compared to mid-20th century levels, including 5% in Sitka, 6% in Fairbanks and Nome, and up to 8% in Anchorage and Utqiaġvik (formerly known as Barrow; Figure 26.8).[238]

Energy Needed for Heating Decreases Across Much of Alaska

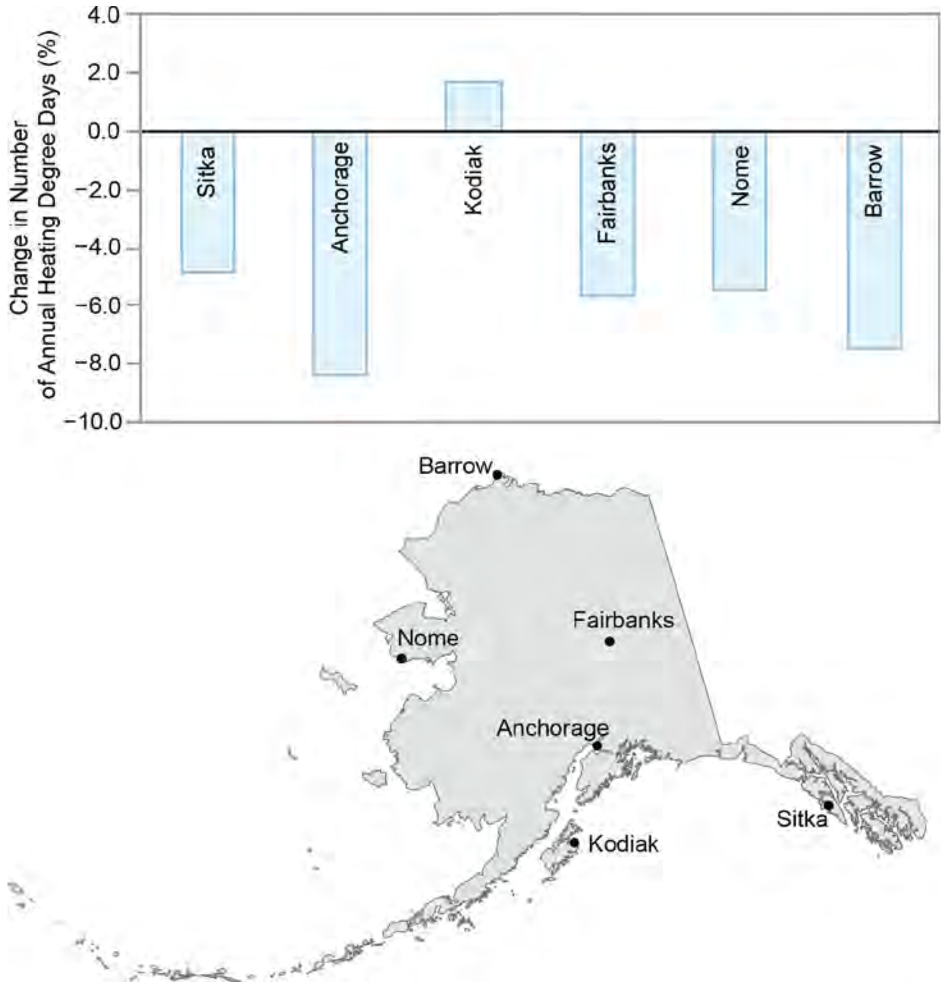


Figure 26.8: The chart shows the percentage change in annual heating degree days for the period 2000–2015 (as compared to 1950–1979) for six Alaska communities. Every 1% decline in heating degree days could potentially yield $10 million of annual savings in heating costs. Sources: University of Alaska Anchorage, NOAA NCEI, and ERT Inc.

Unlike in other regions of the United States, increased cooling degree days (a measure of the energy required to cool homes and other buildings) from warmer summer temperatures provide only a small offset to the beneficial effect of lower heating costs. Applying 2017 retail fuel prices to data on energy use for space heating for Alaska regions, annual expenditures for space heating in Alaska are estimated at about $1 billion (in 2015 dollars).[239,240] Future energy prices are highly uncertain, but the figures suggest that every 1% decline in heating degree days could yield $10 million of annual savings in heating costs.

Key Message 6

Adaptation

Proactive adaptation in Alaska would reduce both short- and long-term costs associated with climate change, generate social and economic opportunity, and improve livelihood security. Direct engagement and partnership with communities is a vital element of adaptation in Alaska.

Alaska and its adjacent Arctic areas are experiencing some of the largest climate changes in the United States (Ch. 2: Climate, KM 7).[14] As such, residents, governments, and industry must prepare for and adapt to the changing climate and associated environmental changes if the most severe impacts are to be avoided.[187,188,241]

Adaptation is often defined as an adjustment in human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects[242] and is an iterative, ongoing process that involves assessment and redirection as needed (Ch. 28: Adaptation).[243] Efforts to prepare for and adapt to the impacts of climate change in Alaska can reduce costs associated with the impacts of climate change,[20,91] generate social and economic opportunities,[244,245] and improve livelihood security.[125,246,247,248] Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change [249] and ocean acidification.[250]

Key elements of successful adaptation in Alaska include coordinated consideration of both environmental and social conditions[134] and careful attention to local context; there is no "one-size-fits-all" strategy.[187,188,251] Enhanced communication, coordination, knowledge sharing, and collaboration are important components of adaptation in Alaska. This includes between communities, among scientists and communities, and across government bodies at the tribal, community, borough, state, and national levels.[251,252,253,254,255,256,257] Building adaptation solutions in partnership with local knowledge is vital for ensuring that adaptations meet local needs and priorities.[254,258,259,260,261]

A range of adaptations to changing climate and related environmental conditions are underway in Alaska, and others have been proposed as potential actions.[135] These adaptations involve human health and poverty alleviation,[136,188] livelihood security,[125] ecosystem management,[262] new construction designs for housing,[263] and a host of other options.[135] Some of these measures reduce vulnerability and risk, while others involve more systemic institutional transformation.[255,260]

At the federal level, there are several key motivations for Arctic Strategies created by various U.S. Government agencies, including 1) recognizing the need to adapt to a changing climate, 2) identifying critical research gaps, 3) creating a vision for regional resilience, and 4) acknowledging the need to safeguard national security under changing environmental conditions.[264,265,266]

Climate change action plans and vulnerability assessments have been completed by several municipalities in Alaska.[135] Formal tribal adaptation planning and preliminary planning activities such as workshops, trainings, webinars, monitoring, and vulnerability assessments have been conducted throughout the state. As of this writing, three climate adaptation plans have been completed and three additional projects are underway to produce climate adaptation plans (Figure 26.9).[8] The Bureau of Indian Affairs awarded eight Climate Resilience Program Awards for adaptation planning between 2013 and 2019.[8] Research has identified 31 adaptation planning-related trainings (2012–2017) and 43 meetings, workshops, and summits (1998–2017).[8] The state-funded Alaska Climate Change Impact Mitigation Program provides funding for hazard mitigation planning, including climate-related hazards such as flooding, coastal erosion, and permafrost thaw.[8,135]

Adaptation Planning in Alaska

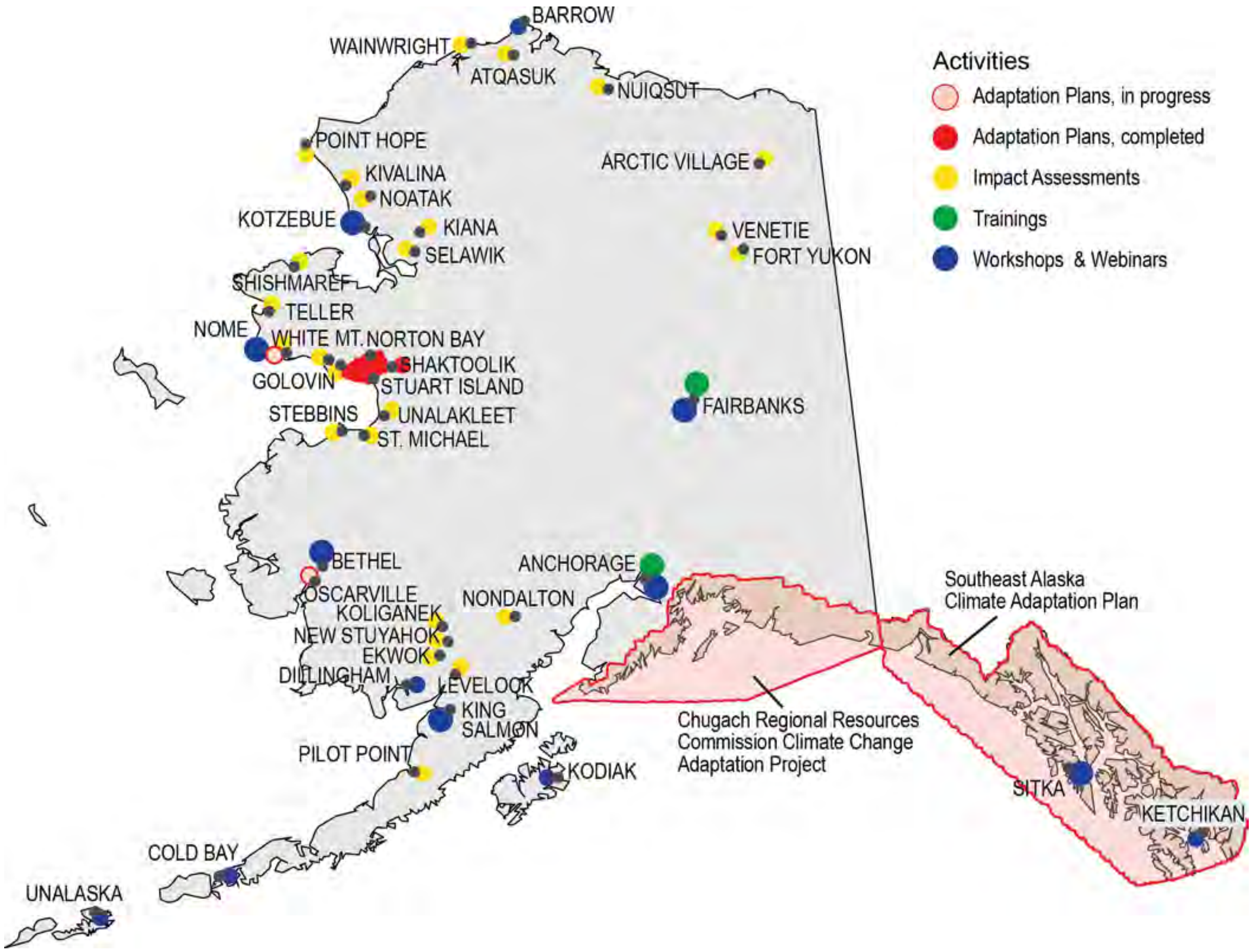


Figure 26.9: The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;[4] the University of Alaska for invasive species;[5] and the Alaska Native Tribal Health Consortium for local observations of environmental change.[6] Additional examples of community-based monitoring can be found through the website of the Alaska Ocean Observing System.[7] Source: adapted from Meeker and Kettle 2017.[8]

In contrast to planning and research, action in response to climate change involves active implementation of plans, changes in policy, protocol, or standard operating procedures, as well as direct reaction to hazards.[135] In the wildfire management and response sector in Alaska, adaptations include establishment of new suppression crew training, evolution of tools used to suppress fire, change in the statutory start date of fire season, and the implementation of community wildfire protection plans.[135]

Several communities in Alaska face immediate threats from climate-related environmental changes, the most severe of which is erosion and coastal inundation related to permafrost thaw and lack of sea ice during fall and winter storms.[122,267] Short-term disaster risk management, such as shoreline revetment, is thus part of adaptation in Alaska.[242] Longer-term planning and village relocation efforts are also underway in two villages but face significant hurdles.[268,269]

Creating decision support tools, establishing climate services and knowledge networks, and providing data sharing and social media have been proposed as additional methods for adapting to the effects of climate change in Alaska.[219,270,271,272,273] Tools that can identify and evaluate policy options under a range of scenarios of future conditions are particularly beneficial in the Arctic, including Alaska.[274,275]

Examples of decision support tools in the state include the Historical Sea Ice Atlas and the SNAP (Scenarios Network for Alaska + Arctic Planning) climate-outlook community charts[276] of projected temperature and precipitation for each community in Alaska. Periodically evaluating decision support tools helps to ensure their usefulness to stakeholders in practical decision contexts.[277]

The use of technology can facilitate the creation and expansion of knowledge networks through events such as webinars[278,279] and social media, such as the newly established AdaptAlaska.org portal and the Local Environmental Observer (LEO) Network that connects people through information, both locally and internationally.[6] Data sharing can be accomplished with online tools such as portals and data hubs; however, the isolated nature of remote, rural communities in Alaska constrains internet connectivity. In addition, technological solutions alone are insufficient to fully meet the information needs of rural communities in the region.[253,271]

A range of climate adaptation guidebooks exist that focus on climate adaptation planning in Alaska and neighboring Canada, which faces related adaptation challenges.[134] These guidebooks have been created by universities, governments, and nongovernmental organizations for a range of audiences, including rural Native Alaska communities, local governments, and state governments. Consistent across the majority of the guidebooks are key phases in the adaptation planning process that include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities (Ch. 28: Adaptation).[134]

Acknowledgments

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Traceable Accounts

Process Description

The Alaska regional chapter was developed through public input via workshops and teleconferences and review of relevant literature, primarily post 2012. Formal and informal technical discussions and narrative development were conducted by the chapter lead and contributing authors via email exchanges, teleconferences, webinars, in-person meetings, and public meetings. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. The author team also engaged in targeted consultations during multiple exchanges with contributing authors, who provided additional expertise on subsets of the Traceable Account associated with each Key Message.

Key Message 1

Marine Ecosystems

Alaska's marine fish and wildlife habitats, species distributions, and food webs, all of which are important to Alaska's residents, are increasingly affected by retreating and thinning arctic summer sea ice, increasing temperatures, and ocean acidification. Continued warming will accelerate related ecosystem alterations in ways that are difficult to predict, making adaptation more challenging (*very likely*, *very high confidence*).

Description of evidence base

Changes in arctic sea ice and its impacts on marine ecosystems and various biological resources are well documented by 38 years of satellite records[280] and the scientific literature.[48,50,51,77,78,79,281] The finding of a continuing retreat of arctic sea ice is supported by sea ice modeling and continued CO_2 emissions.[37,46] The northward distribution of ocean fish species is documented by numerous scientific papers: see Perry et al. (2005),[282] Thorsteinson and Love (2016),[17] and Mecklenburg et al (2002).[72] The impacts of an increased open Arctic sea contributing to increases in ocean acidification[18] and expanding deeper into the Arctic Basin[57] will need validation with further studies.

Major uncertainties

To date, relatively few of Alaska's marine species have been studied for their response to ocean acidification, and the assessment of potential impacts is challenging due to each species' differing habitats, life cycle stages, and response and adaptation mechanisms. It is known that some organisms respond more dramatically to environmental change than others, and warming ocean temperatures may be more significant in the short term than ocean acidification. There is significant uncertainty in the projected increase of shipping through the Arctic and the Bering Strait, since much of this increase will be driven by economic factors and not climate or other environmental change.

Description of confidence and likelihood

There is *very high confidence* that the arctic sea ice will continue to reduce in size over the next 20–40 years, and it is *likely* that the Arctic Ocean will be nearly ice-free in late summer by mid-century based on current climate models. There is also *high confidence* that this melting will have an effect on the northward expansion of North Pacific fish species and associated effects on associated food webs. There is *very high confidence* that continued melting of the Arctic Ocean ice will have an effect on the habitat and behavior of polar bear and walrus. There is *high confidence* that Alaska's ocean waters are becoming increasingly acidic. Given this increase, it is *very likely* that there will be biological impacts, but it is uncertain which species will be affected and to what extent.

Key Message 2

Terrestrial Processes

Alaska residents, communities, and their infrastructure continue to be affected by permafrost thaw, coastal and river erosion, increasing wildfire, and glacier melt. These changes are expected to continue into the future with increasing temperatures, which would directly impact how and where many Alaskans will live (*very likely*, *high confidence*).

Description of evidence base

Permafrost

Multiple studies of permafrost in Alaska have shown that the gradual warming of the ground[105] has resulted in the warming and thawing of permafrost over the past 30 years,[79,104,106] and spatial modeling projects that near-surface permafrost will potentially disappear on up to a quarter of the landscape by the end of the 21st century.[108] The magnitude of these changes depends on climate and ground-ice conditions, where permafrost thaw generally results in drier upland habitat and wetter lowlands as tundra and forests are converted to lakes and bogs.[106,283] These changes will undoubtedly result in a number of societal consequences, loss of wildlife habitat, damage to infrastructure (including buildings, airport runways, tank farms, and roads), ecosystem contamination, and increased maintenance costs.[20,21,91,207,284,285]

Wildfire

It has been well documented that wildfires are a common occurrence in Alaska, especially the interior boreal areas, although they have also occurred in areas of arctic tundra,[114,286] with some of the largest fire years (1–6 million acres) occurring between 2004 to 2016 since records began around 1950.[114] Recent studies show that changes in wildfire across the Alaska landscape could be attributed to human activity.[287] This has resulted in changes in boreal vegetation cover[95,96] and tundra communities.[286] The increased fire frequency of recent decades is expected to continue into the future, in spite of the change to less flammable deciduous vegetation, because of the accompanying change to warmer and drier conditions.[95] The ground is warmer under post-fire deciduous vegetation, and thus fires will enhance the thaw of permafrost that is already underway due to climatic warming.[288]

Coastal and River Erosion

The shoreline along Alaska's northern coast has eroded at some of the fastest rates in the Nation, putting local communities, oil fields, and coastal habitat at risk.[19] Unlike the contiguous United States, Alaska is subject to glacial and periglacial processes that make permafrost and sea ice key controlling factors of coastal erosion and flooding. Thermal degradation of permafrost leads to enhanced rates of erosion along permafrost-rich coastal shorelines[19] and subsidence of already low-lying regions. Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of more shoreline in the future.[19]

While erosion and changed river courses are a normal part of landscape evolution, lateral river erosion rates are likely to change over time, but the direction and magnitude of these changes are poorly understood. Major river erosion events are typically tied to high hydrological flows or the melting of permafrost along river and stream banks. Statewide, evidence for changes in maximum gauged streamflows is mixed, with a majority of locations having no significant trend.[289] There is significance for seasonal changes in the timing of peak flows in interior Alaska, though increases in the absolute magnitude are not well evident in existing data.[290] Riverine erosion is a serious problem for a significant number of communities.[123] Significant resources have been expended to slow erosion at some communities, often through the construction of berms and bank stabilization projects. These projects have a mixed record of success and nearly always require ongoing maintenance.

Glacier Change

Airborne altimetry surveys of Alaska glaciers spanning the 1994–2013 interval and covering about 40% of the region's glacierized area[137] yield decadal timescale mass balance estimates for individual glaciers and a regional estimate.[291] Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,[139,140,141,142] with substantial regional-scale reductions in glacier area, volume (up to 40%–60% loss), and number. Moreover, physically based runoff models suggest that runoff from glaciers accounts for almost 40% of the total freshwater discharge into the Gulf of Alaska.[292]

Interdisciplinary research along the Gulf of Alaska is providing new insights into the role of glacier runoff in structuring downstream freshwater and nearshore marine ecosystems.[101] End-of-century projections from physically based models suggest that anticipated atmospheric warming (2°–4.5°C) will drive volume losses of 32%–58% for Alaska glaciers.[142] Increases in river chemical ions due to glacial runoff and permafrost melt have also been associated with diminishing glaciers in Alaska.[94,291]

Major uncertainties

Some events such as wildfires and coastal storms are dependent on regional and local current weather conditions, and the exact landscape or ecosystem response can be highly variable. Future effects are also dependent on quick response actions and adaptation measures.

Description of confidence and likelihood

There is *high confidence* that wildfire in Alaska will continue but *medium confidence* as to its ultimate effect on vegetation and permafrost, which is often dependent on fire fields available (e.g., older forests or new growth shrublands), the fire intensity, and the return rate. There is *high confidence* that the north coast of Alaska is eroding at high rates. It is *likely* that coastal erosion is accelerating in response to climate change but *medium to low confidence* as to the location and rate because of limited studies and datasets documenting this. There is *high confidence* that river erosion will continue but *medium confidence* as to when, where, and to what extent this will occur across Alaska because of differences in local climatic and geographic qualities of the area in question. There is *high confidence* and it is *likely* that the glaciers in Alaska will continue to diminish, especially those that are tidewater glaciers.

Key Message 3

Human Health

A warming climate brings a wide range of human health threats to Alaskans, including increased injuries, smoke inhalation, damage to vital water and sanitation systems, decreased food and water security, and new infectious diseases (*very likely*, *high confidence*). The threats are greatest for rural residents, especially those who face increased risk of storm damage and flooding, loss of vital food sources, disrupted traditional practices, or relocation. Implementing adaptation strategies would reduce the physical, social, and psychological harm likely to occur under a warming climate (*very likely*, *high confidence*).

Description of evidence base

The evidence base for climate-related health threats can be divided into three main categories. First are those threats that have strong documentation of both the climate or environmental driver and the health effect. An example is the emergence of gastrointestinal illness due to the northward expansion of the bacteria *Vibrio parahaemolyticus* among Alaska shellfish. Other threats with a similar level of evidence include increased venomous insect stings.

Second, some health threats are based on a combination of well-documented climate-driven environmental changes and records of anecdotal community observations of health impacts. Examples include the increased risk of injury or death from exposure among winter subsistence-related travelers or respiratory problems from smoke inhalation during wildfires. The community observations of these threats point to a real trend.[10,158] However, there is no historical or current means to document and track such injuries or exposures. Therefore, objective evidence, such as increased rates of occurrence or peer-reviewed reports, is not currently available. Other threats that fit this category include respiratory symptoms from dust and pollen, decreased food security, and loss of cultural and traditional lifestyles and practices along with the accompanying mental health or social disruption effects.

The third category is those threats that are logical inferences of potential health risks based on documented environmental changes and community-vulnerability assessments. Examples include the well-documented threats from coastal storms to community infrastructure and shorelines and the damage to community water and sanitation systems from permafrost thawing or erosion. The risk of physical harm from major storm or flooding events is obvious, and the loss of a water/sewer system would likewise pose a clear threat to health through waterborne or water-washed infections. However, these threats are based on likely outcomes from existing trends in environmental change. The human health effects are either undocumented or are anticipated in the future. Many of the infectious disease risks and harmful algal blooms (HABs) fall into this category; where range expansion of pathogens or vectors is occurring, health effects are likely to follow.

Major uncertainties

The greatest uncertainties in the health threats of climate change lie in the geographic distribution, magnitude, duration, and capacity to detect the effects. Many of the impacts of climate changes are most evident in rural Alaska, which is an enormous area and sparsely populated. Thus, sporadic events with geographic variability such as storms or HABs may have a range of human health effects from none to severe, depending on the timing and location of exposure. Likewise, the magnitude and duration of the effects on health are difficult to predict based on variability in the source of risk and human adaptation. The lack of repeated outbreaks of *V. parahaemolyticus* illnesses from raw shellfish consumption is a good example of how adaptations in aquaculture practices and commercial regulations, along with likely changes in consumer practices, appear to have reduced the magnitude of the health threats, compared with initial outbreak. Finally, we have limited capacity to detect many of the health outcomes associated with climate change. The organized reporting and monitoring of climate-linked health effects by public health are limited to the toxin-mediated illnesses, some of the infectious diseases, mortality events, and unusual clusters of illnesses or injuries. Even among those conditions, underreporting of illnesses is common due to healthcare-seeking behavior, lack of recognition by medical providers due to unfamiliarity or limited diagnostic capacities, or incomplete compliance. For many of the anticipated health effects, such as nonoccupational injuries, mental health issues, and respiratory conditions, there may be documentation in a person's individual health records, but no systems are in place to collect such information and link these illnesses to climate or environmental events or conditions. Large administrative healthcare databases, such as the Alaska Hospital Discharge Data System or the Alaska Health Information Exchange, could be used for focused investigations or ongoing monitoring. However, these would only be useful for severe illnesses with large geographic or multiyear distributions. These datasets would likely miss health events that do not result in emergency room visits or hospitalizations, that are rare, or that occur in irregular episodes. Data from ambulatory clinic visits, community surveys, or syndrome-based surveillance efforts would be needed to detect and characterize uncommon or less severe health occurrences.

Description of confidence and likelihood

There is *high confidence* that there will be a continuation of trends causing higher winter temperatures, increased storm events, increased frequency and extent of wildfires, and increased permafrost thawing with associated erosion. Given these trends, there is *very likely* to be subsequent human health effects, but the distribution and magnitude of these effects remain uncertain.

Key Message 4

Indigenous Peoples

The subsistence activities, culture, health, and infrastructure of Alaska's Indigenous peoples and communities are subject to a variety of impacts, many of which are expected to increase in the future (*likely*, *high confidence*). Flexible, community-driven adaptation strategies would lessen these impacts by ensuring that climate risks are considered in the full context of the existing sociocultural systems (*likely*, *medium confidence*).

Description of evidence base

Many studies have examined different aspects of Alaska's Indigenous communities, including the ways climate change is affecting or can affect subsistence,[15,26,28,29,30,125,131,194,197,198,293] culture,[125,182,184] health,[27,29,294] and infrastructure.[20,21,164,295] Alaska's Indigenous peoples are increasingly involved in the research efforts, not just as informants or assistants but as those shaping and asking research questions and as those analyzing and interpreting the results of studies.[27,29,125,190] As a result, research on the impacts of climate change on Alaska's Indigenous peoples is increasingly focused on topics of direct relevance to daily lives and long-term/historical interests and is increasingly attentive to the context in which those changes occur. In other words, there is increasing confidence that the right questions are being asked and the answers are being interpreted in the right way.[29,125]

Major uncertainties

There is little question that climate change is having widespread and far-reaching impacts on Alaska's Indigenous peoples. It is less clear, however, exactly which peoples and communities are responding to the changes they face. One community may be able to seize a new opportunity or may be able to adjust effectively to at least some forms of change, whereas another community will not be able to do either. More needs to be understood about these differences, the reasons for them, and how adaptability and resilience can be fostered.

It is also unclear how, exactly, the changes will influence one another as they occur in the context of all that is happening in Alaska Native life. For example, climate change may mean hunters have to travel farther to hunt. GPS allows for more reliable navigation, and four-stroke engines provide more confidence when traveling farther offshore. At the same time, rising fuel prices mean it is more expensive to travel far, perhaps limiting the ability of a hunter to take advantage of better navigation and motors. How these competing influences will balance out is difficult to say and requires more attention.

Description of confidence and likelihood

There is *high confidence* that climate change is having far-reaching effects on Alaska's Indigenous peoples. It is *likely* that most of these impacts will have negative effects, as they undermine existing behaviors, patterns, infrastructure, and expectations. It is also *likely* that there will continue to be some benefits and opportunities stemming from climate-related changes. There is *medium confidence* that the negative impacts can be reduced and the new opportunities maximized with appropriate policy and regulatory action, as not all aspects of change can be addressed in this way, and it is unclear whether such a systematic approach is plausible in light of the way programs and policies are administered in Alaska's Indigenous communities.

Key Message 5

Economic Costs

Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska (*very likely*, *high confidence*). It is also reducing heating costs throughout the state (*likely*, *medium confidence*). These effects are very likely to grow with continued warming (*very likely*, *high confidence*). Timely repair and maintenance of infrastructure can reduce the damages and avoid some of these added costs (*likely*, *high confidence*).

Description of evidence base

Coastal erosion affects a number of coastal communities, with the highest rates on the Arctic coastline.[19] Coastal erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.[123] Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office (GAO) study ranged from $80 to $200 million per community.[122]

Melting glaciers will increase the role of seasonal precipitation patterns for hydroelectric power generation. River discharge has been increasing during the winter since the 1960s, but because reservoirs are generally full in fall, investments to increase reservoir heights would be required to take advantage of increased fall precipitation.[145]

National Weather Service (NWS) daily weather summaries show that heating degree days have already declined by 5% in Sitka, 6% in Fairbanks and Nome, and 8% in Anchorage and Utqiaġvik (formally known as Barrow) as compared to mid-20th century levels. The same NWS data show that increased cooling degree days from warmer summer temperatures provide only a small offset to the beneficial effect of lower heating costs.

Major uncertainties

The extent, rate, and patterns of coastal erosion at locations other than along the north coast, and including deltas and rivers, are poorly known. Change in the patterns and trends of erosion (for example, an increase in the rate associated with warming and climate change), is expected but poorly documented for most locations due to the scarcity of historical data.

Future energy prices are highly uncertain, generating a high level of uncertainty around the dollar value of the savings in space heating costs associated with the projected decline in heating degree days.

Wildfire suppression costs depend on future policy decisions for wildfire management. Property damage from wildfire depends on uncertain future settlement and development patterns.

Description of confidence and likelihood

There is *high confidence* and it is very likely that future damage to infrastructure from thawing permafrost and coastal erosion will cost hundreds of millions of dollars annually to repair or replace. There is *high confidence* and it is *likely* that timely repair and maintenance of infrastructure can reduce damages and avoid some of the added costs. There is *medium confidence* and it is *very likely* that these costs will be offset in part by savings from reduced space heating needs.

Key Message 6

Adaptation

Proactive adaptation in Alaska would reduce both short- and long-term costs associated with climate change, generate social and economic opportunity, and improve livelihood security (*likely*, *high confidence*). Direct engagement and partnership with communities is a vital element of adaptation in Alaska (*likely*, *very high confidence*).

Description of evidence base

Research investigating costs of adapting to projected climate changes in Alaska in the realms of public infrastructure and wildfire suppression indicates cost savings from adaptation.[21,91] Rural Alaska communities have high reliance on subsistence food resources. Access to these resources, as well as their habitat and migration patterns, is impacted by several factors, including climate change. Adaptation is thus important for maintaining livelihood security in these communities.[125,246,247,248] Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change[249] and ocean acidification.[250] Rural communities in Alaska share many climatic, cultural, and ecosystem properties with rural communities across the Arctic. Research in Canada has documented the social and economic opportunities from adaptation in Northern communities.[244,245]

Adaptation actions to the impacts of climate change in Alaska have been transitioning from awareness and concern to education and actions.[135,251] There are a number of documents that describe climate change related research needs and actions associated with infrastructure, economics, hazards and safety, and terrestrial ecosystem impacts, as well as other concerns of rural Alaska Native communities.[8,135,252,271] Adaptation actions that address these same needs have also been described in Canada and the circumpolar Arctic.[135] The importance of direct engagement and partnership with communities in adaptation is emphasized throughout the literature.[125,187,205,252,253,254,258,259,260,261,271,296,297]

Most research reports on case studies and actions that describe transparent, collaborative, and accessible information though data sharing, building of networks, and long-term partnerships with communities.[252,253,254,260,261] Climate change has also been described as a risk management problem, with proposed actions that address risk and inform risk management actions being offered.[255]

A number of climate adaptation guidebooks focus on Alaska and Canada, which have related adaptation challenges.[134] Universities, governments, and nongovernmental organizations produced these guidebooks for a range of audiences, including rural Alaska Native communities, local governments, and state governments. Key phases in the adaptation planning process that are consistent across the majority of the guidebooks include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities.[134] Guidebooks specific to Alaska Natives and Canadian Inuit and First Nations peoples emphasize the importance of community support and participation in the adaptation planning process.[134]

Major uncertainties

Little research has been conducted to track and evaluate the efficacy of implementation of existing adaptation planning in Alaska or to assess the possibilities for maladaptation. Similarly, the feedbacks and synergies are not well documented between adaptation and changes in physical, natural, and social systems. More research is needed to understand cross-sector and cumulative impacts and how they can best be addressed in an all-inclusive manner.[135]

Description of confidence and likelihood

There is *high confidence* that proactive adaptation can reduce costs, generate social and economic opportunity, and improve livelihood security. It is *likely* and there is *high confidence* that proactive adaptation will be affected by external factors, such as global markets that are beyond the control of the organization or institution implementing the adaptations.

It is *likely* and there is *very high confidence* that direct engagement and partnership with communities will be a critical element of adaptation success, as this has strong evidence and high consensus in the literature; however, there are a limited number of publications that document this partnership model in Alaska.

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

27 Hawai‘i and U.S.-Affiliated Pacific Islands

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27 Hawaiʻi and U.S.-Affiliated Pacific Islands

Honolulu, Hawaiʻi

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures, changing rainfall patterns, sea level rise, and increased risk of extreme drought and flooding. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism. Terrestrial habitats and the goods and services they provide are threatened by rising temperatures, changes in rainfall, increased storminess, and land-use change. These changes promote the spread of invasive species and reduce the ability of habitats to support protected species and sustain human communities. Some species are expected to become extinct and others to decline to the point of requiring protection and costly management.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economies, housing and energy, transportation, and other forms of infrastructure. By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands. This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience. As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat. Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5).

Key Message 5

Indigenous Communities and Knowledge

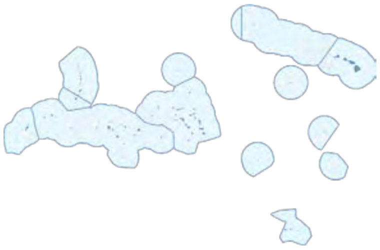
Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources. Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs. In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation.

Executive Summary



The U.S. Pacific Islands are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts.

A prevalent cause of year-to-year changes in climate patterns around the globe[1] and in the Pacific Islands region[2] is the El Niño–Southern Oscillation (ENSO). The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds. It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both

El Niño and La Niña extremes in this century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).[3,4]

On islands, all natural sources of freshwater come from rainfall received within their limited land areas. Severe droughts are common, making water shortage one of the most important climate-related risks in the region.[5] As temperature continues to rise and cloud cover decreases in some areas, evaporation is expected to increase, causing both reduced water supply and higher water demand. Streamflow in Hawai‘i has declined over approximately the past 100 years, consistent with observed decreases in rainfall.[6]

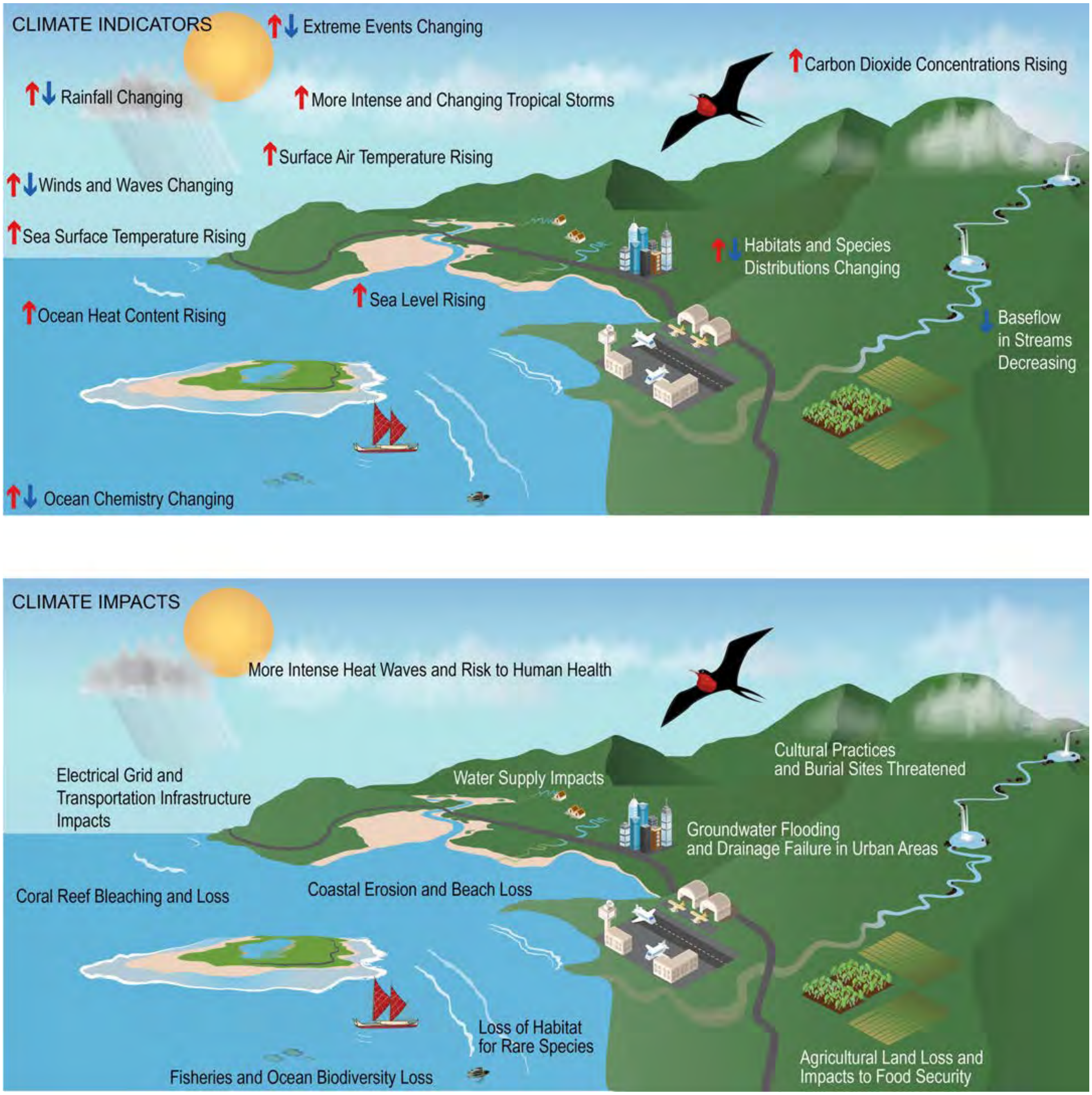
The impacts of sea level rise in the Pacific include coastal erosion,[7,8] episodic flooding,[9,10] permanent inundation,[11] heightened exposure to marine hazards,[12] and saltwater intrusion to surface water and groundwater systems.[13,14] Sea level rise will disproportionately affect the tropical Pacific[15] and potentially exceed the global average.[16,17]

Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function. Inundation of atolls in the coming decades is projected to impact existing on-island ecosystems.[18] Wildlife that relies on coastal habitats will likely also be severely impacted. In Hawai‘i, coral reefs contribute an estimated $477 million to the local economy every year.[19] Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the Hawai‘i and Pacific Islands region will experience annual bleaching before 2050. An ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.[20]

Indigenous communities of the Pacific derive their sense of identity from the islands. Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands. The rich body of traditional knowledge is place-based and localized[21] and is useful in adaptation planning because it builds on intergenerational sharing of observations.[22] Documenting the kinds of governance structures or decision-making hierarchies created for management of these lands and waters is also important as a learning tool that can be shared with other island communities.

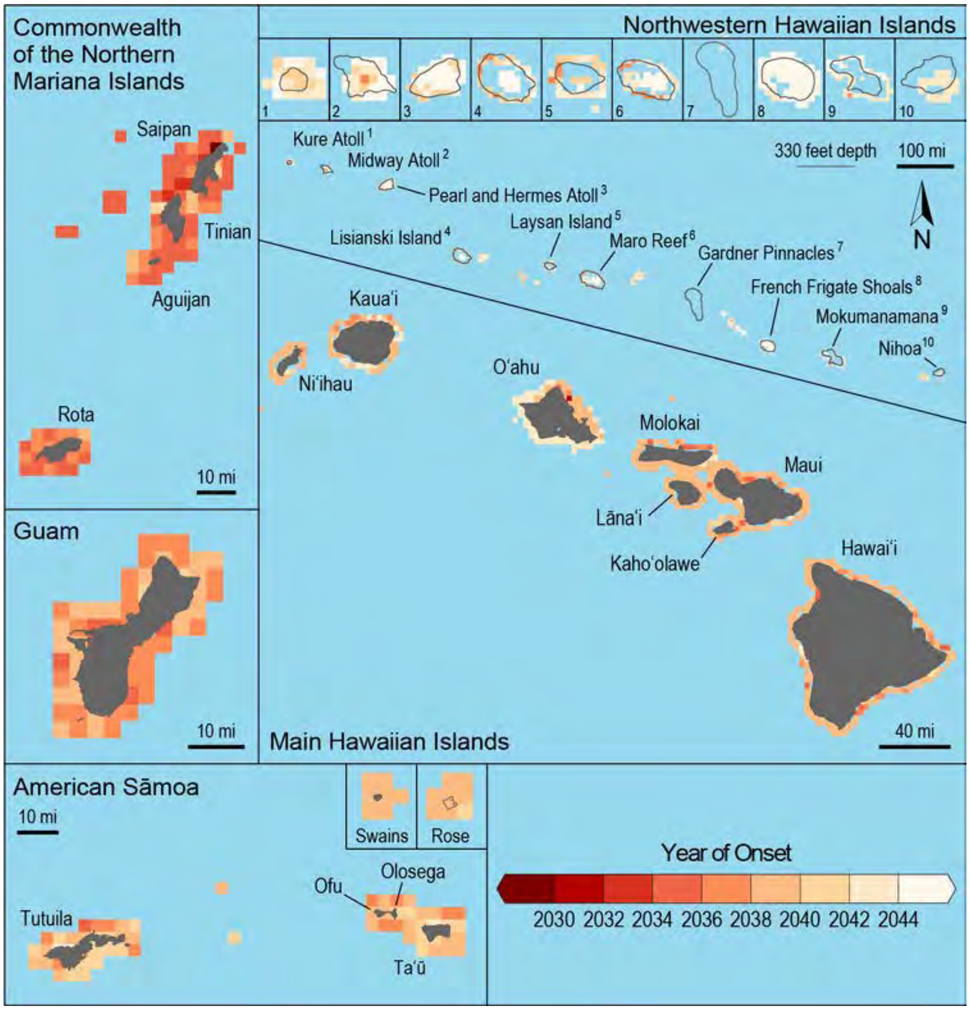
Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation as well as other climate-related impacts. Social cohesion is already strong in many communities, making it possible to work together to take action. Early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

Climate Indicators and Impacts



Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. *From Figure 27.2 (Source: adapted from Keener et al. 2012).*[23]

Projected Onset of Annual Severe Coral Reef Bleaching



The figure shows the years when severe coral reef bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. From *Figure 27.10 (Source: NOAA)*.

Background

The U.S. Pacific Islands (Figure 27.1) are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. The region comprises a vast ocean territory and more than 2,000 islands that vary in elevation, from high volcanic islands such as Mauna Kea on Hawaiʻi Island (13,796 feet) to much lower islands and atolls such as Majuro Atoll in the Republic of the Marshall Islands (the highest point on Majuro is estimated at 9 feet).[24,25,26] Its environments span the deepest point in the ocean (Mariana Trench National Monument) to the alpine summits of Hawaiʻi Island.[23] The region supports globally important marine and terrestrial biodiversity, as well as stunning cultural diversity (over 20 Indigenous languages are spoken).[23]

The U.S. Pacific Islands region is defined by its many contrasting qualities. While the area is a highly desirable tourist destination, with Hawaiʻi and the U.S.-Affiliated Pacific Islands (USAPI) drawing more than 10 million tourists in 2015,[27]

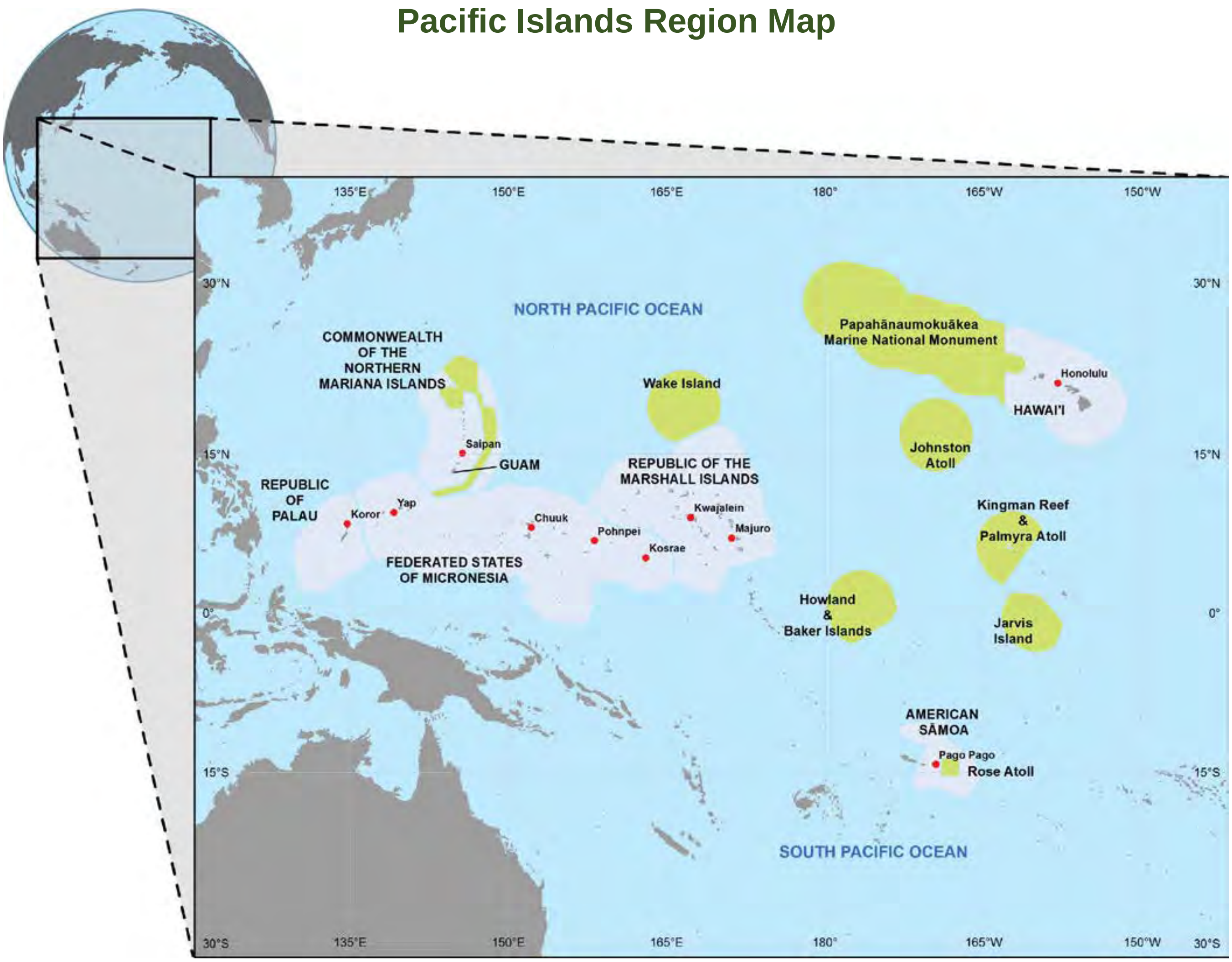


Figure 27.1: The U.S. Pacific Islands region includes the state of Hawaiʻi, as well as the U.S.-Affiliated Pacific Islands (USAPI): the Territories of Guam and American Sāmoa (AS), the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). While citizens of Guam and the CNMI are U.S. citizens, those from AS are U.S. nationals. Under the Compact of Free Association (COFA), citizens from FSM, RP, and RMI can live and work in the United States without visas, and the U.S. armed forces are permitted to operate in COFA areas. On this map, shaded areas indicate the exclusive economic zone of each island, including regional marine national monuments (in green). Source: adapted from Keener et al. 2012.[23]

living in the islands carries climate-related risks, such as those from tropical cyclones, coastal flooding and erosion, and limited freshwater supplies. Because of the remote location and relative isolation of the islands, energy and food supplies are shipped in at high costs.

For example, Hawaiʻi has the highest average electricity rate in the United States (more than twice the national average),[28] and more than 85% of food is imported on most islands (see Ch. 17: Complex Systems and Ch. 20: U.S. Caribbean, Background and KM 5 for more information on the importance of regional supply chains).[29,30,31] Though the islands are small, they are seats for key military commands, with forces stationed and deployed throughout the region providing strategic defense capabilities to the United States.

Despite the costs and risks, Pacific Islanders have deep ties to the land, ocean, and natural resources, and they place a high value on the environmental, social, and physical benefits associated with living there. Residents engage in diverse livelihoods within the regional economy, such as tourism, fishing, agriculture, military jobs, and industry, and they also enjoy the pleasant climate and recreational opportunities. Important challenges for the region include improving food and water security, managing drought impacts, protecting coastal environments and relocating coastal infrastructure, assessing climate-induced human migration, and increasing coral reef resilience to warming and acidifying oceans.

New Research Validates and Expands on Previous Assessment Findings

In previous regional climate assessments, key findings focused on describing observed trends and projected changes in climate indicator variables for specific sectors.[23,32] In many cases, new observations and projections indicate that there is less time than previously thought for decision-makers to prepare for climate impacts. Regionally, air and sea surface temperatures continue to increase, sea level continues to rise, the ocean is acidifying, and extremes such as drought and flooding continue to affect the islands.[33] New regional findings include (Figure 27.2)

- a limited set of detailed statistical and dynamical downscaled temperature, rainfall, and drought projections for Hawaiʻi (unlike the 48 contiguous states, Hawaiʻi—like the Alaska and U.S. Caribbean regions—does not have access to numerous downscaled climate projections; see Key Messages 1 and 6);[34,35,36]
- projected future changes to winds and waves due to climate change, which affect ecosystems, infrastructure, freshwater availability, and commerce (see Key Message 3);[37,38]
- more spatially refined and physically detailed estimates showing increased sea level rise for this century (see Key Messages 3 and 6);[17,39]
- models of how central Pacific tropical cyclone tracks are shifting north (see Key Message 3);[40]
- identification of urbanized areas vulnerable to flooding from rising groundwater and erosion (see Key Messages 1, 3, and 6);[8,41]
- detailed assessment of vulnerability to sea level rise in Hawaiʻi (see Key Message 3);[42]
- climate vulnerability assessments for endemic and endangered birds and plants showing shifting habitats (see Key Messages 2 and 5);[43,44] and
- projections that corals will bleach annually throughout the entire Pacific Islands region by 2045 if current warming continues (the worst bleaching event ever observed occurred during the El Niño of 2015–2016; Key Messages 4 and 6).[45,46,47,48]

Climate Indicators and Impacts

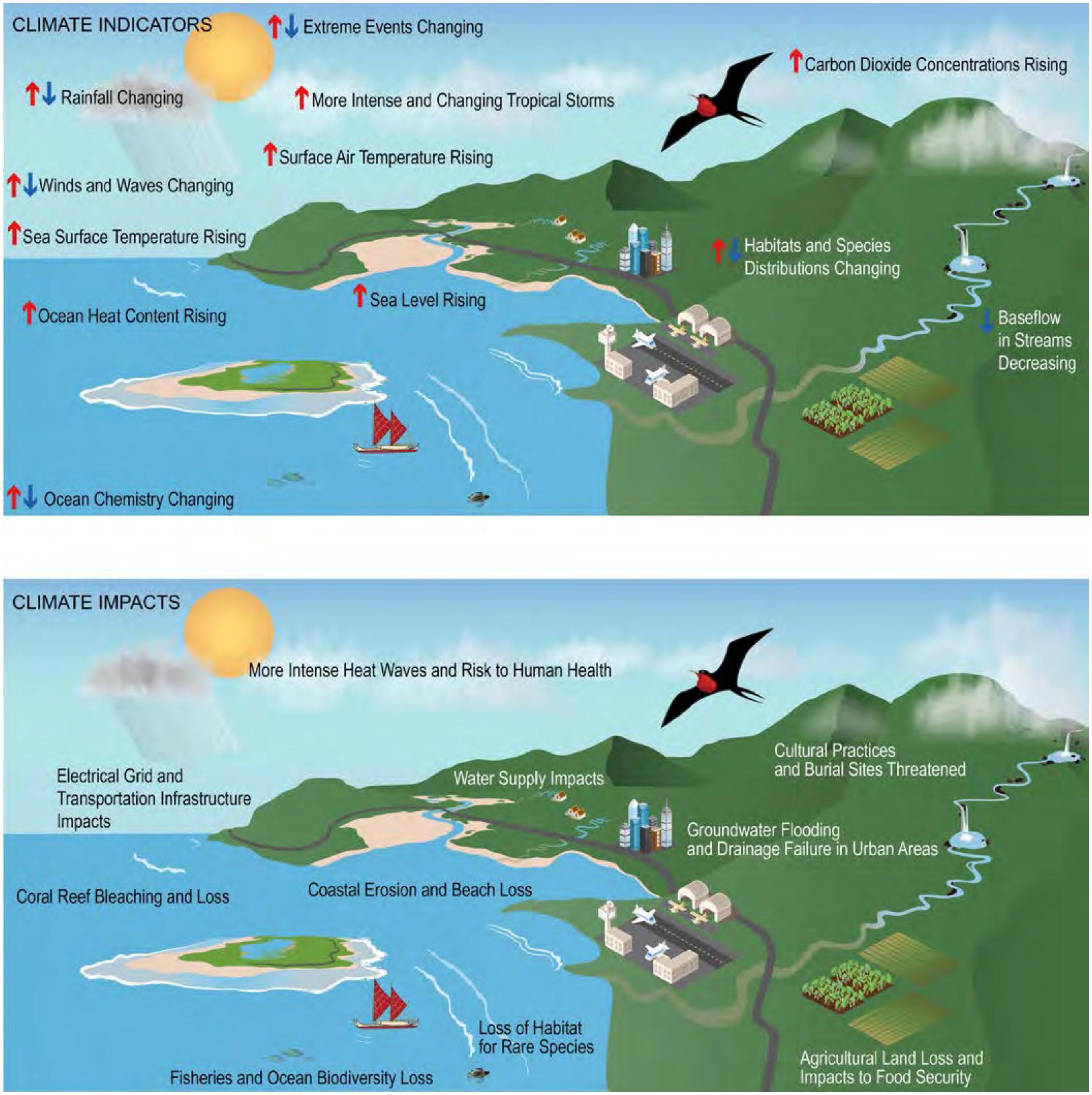
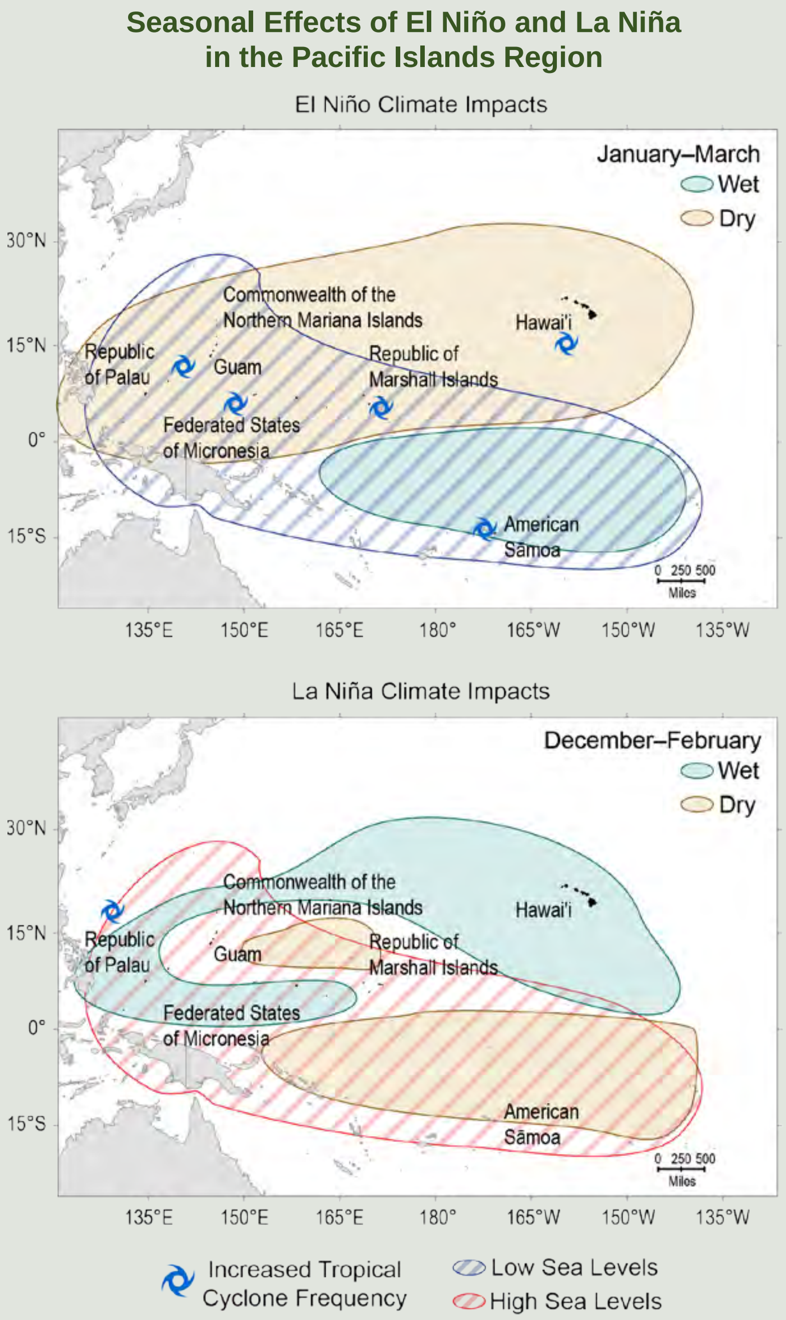


Figure 27.2: Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the Hawai‘i and U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. Source: adapted from Keener et al. 2012.[23]

Box 27.1: El Niño–Southern Oscillation (ENSO) and Year-to-Year Climate Variability

The El Niño-Southern Oscillation (ENSO) phenomenon is a prevalent cause of year-to-year changes in climate patterns globally[1] and in the Pacific Islands region.[2] The effects of ENSO can be magnified when it is in phase with longer periodic cycles such as the Pacific Decadal Oscillation and the Interdecadal Pacific Oscillation.[49] The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds (for details about the different patterns of global climate variability, see Perlwitz et al. 2017).[1]

Figure 27.3 shows how the typical seasonal patterns of rainfall, sea level, and storminess in El Niño and La Niña play out across the region, during which severe droughts can occur in the central and western Pacific and large areas of coral reefs can experience bleaching.[50,51] The strength of these ENSO-related patterns in the short term can make it difficult to detect the more gradual, long-term trends of climatic change. Understanding and anticipating ENSO effects, however, is important for planning for climate impacts on island communities and natural resources. Already, increases in the strength of El Niño and La Niña events have been observed (though the link between these observed changes and human causes is unclear).[3,52] It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both El Niño and La Niña extremes in the 21st century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).[3,4]


Seasonal Effects of El Niño and La Niña in the Pacific Islands Region

El Niño Climate Impacts

La Niña Climate Impacts

Figure 27.3: A prevalent cause of year-to-year changes in climate patterns in the U.S. Pacific Islands region is the El Niño–Southern Oscillation (ENSO) phenomenon. These maps show how (top) El Niño and (bottom) La Niña most commonly affect precipitation, sea level, and storm frequency in the Pacific Islands region in the year after an ENSO event. During certain months in the boreal (northern) winter, El Niño and La Niña commonly produce patterns that are different from those following an ENSO neutral year. After an El Niño, islands in the central Pacific (such as Hawai‘i) and islands in the western Pacific (such as the Republic of Palau and Guam) experience drier than normal conditions from January to March, while the western and southern Pacific see abnormally low sea levels. After a La Niña, the patterns are reversed and occur earlier (December through February).[50] Source: East-West Center.

Risks and Adaptation Options Vary with Geography

In the U.S. Pacific Islands region, the severity of the impacts of climate change differ among communities. A number of factors affect both the level of risk and a community's approach to responding to that risk: geography (for example, high-elevation islands versus low-elevation atolls), the proximity of critical infrastructure to the coast, governance structure, cultural practices, and access to adaptation funding. As in the U.S. Caribbean (see Ch. 20: U.S. Caribbean), climate change is projected to impact the U.S. Pacific Islands through changes in ecosystem services, increased coastal hazards, and extreme events. Adaptation options in both regions are unique to their island context and more limited than in continental settings.

While uncertainty will always exist about future climate projections and impacts, communities and governments in the U.S. Pacific Islands region are planning proactively. Already, policy initiatives and adaptation programs are significant and include the accreditation of the Secretariat of the Pacific Regional Environment Programme (SPREP) to the Green Climate Fund,[53] the passage of the Hawaiʻi Climate Adaptation Initiative Act,[54] and the creation of separate climate change commissions for the City and County of Honolulu (established 2018) and the State of Hawaiʻi (established 2017). To increase coordination of adaptation and mitigation initiatives across the region and foster future climate leadership, island nations and the State of Hawaiʻi signed the Majuro Declaration.[55] These initiatives are moving adaptation science forward, for example, by increasing freshwater supply, upgrading vulnerable infrastructure, and creating legal frameworks for state and local governments to build climate resilience into current and future plans and policies.

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures, changing rainfall patterns, sea level rise, and increased risk of extreme drought and flooding. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

On islands, all natural sources of freshwater come from rainfall received within their limited land areas. Piping water from neighboring states is not an option, making islands uniquely vulnerable to climate-driven variations and changes in rainfall, rates of evaporation, and water use by plants. The reliability of precipitation is a key determinant of ecosystem health, agricultural sustainability, and human habitability.

Severe droughts are common, making water shortage one of the most important climate-related risks in the region.[5] In water emergencies, some islands rely on temporary water desalination systems or have water sent by ship, both of which are costly but life-saving measures (Figure 27.4).[56] Droughts occur naturally in this region and are often associated with El Niño events. Rainfall in Hawaiʻi and the U.S.-Affiliated Pacific Islands (USAPI) is strongly affected by seasonal movement of the intertropical convergence zone and ENSO (see Box 27.1). Similarly, other patterns of climate variability, such as the Pacific Decadal Oscillation, produce strings of wet or dry years lasting decades in the region. Because of this natural

Emergency Drought Response Action for Island Residents

Figure 27.4: U.S. Navy sailors unload reverse osmosis water supply systems in the Republic of the Marshall Islands in 2013 to provide relief from severe drought. The systems will produce potable water for more than 15,000 Ebeye Island residents. Photo credit: Mass Communication Specialist 2nd Class Tim D. Godbee, U.S. Navy.

variability, including dry seasons and frequent dry years, Pacific islands are highly vulnerable to any climate shifts that reduce rainfall and increase the duration and severity of droughts.

Compounding the direct effects of climate change, such as changing rainfall patterns, are the impacts of sea level rise on groundwater and groundwater-fed surface environments, such as wetlands and open lakes and ponds in low islands. For atoll islands, residents depend on shallow aquifers for some of their domestic water needs and for food production.[57] Rising sea level leads to a higher frequency of overwash events,[58] during which seawater inundates large parts of the islands and contaminates freshwater aquifers, wetlands, and other aquifer-fed environments. Overwash events already periodically occur during unusually high tides as a result of storm-driven waves or because of tsunamis. Rising sea level greatly increases the risk of groundwater contamination when these events occur.

Climate shifts have already been observed in the region, with increases in temperature and changes in rainfall. In Hawaiʻi, temperature has risen by 0.76°F over the past 100 years (Figure 27.5),[59] and 2015 and 2016 were the warmest years on record. Higher temperatures increase evaporation, reducing water supply and increasing water demand. Hawaiʻi rainfall has been trending downward for decades, with the period since 2008 being particularly dry.[60] These declines have occurred in both the wet and dry seasons and have affected all the major islands (Figure 27.6). In Micronesia, rainfall has generally decreased in the east, remained steady for some islands in the west (for example, Guam), and increased for other islands in the west.[23,32,61,62]

The set of global and regional climate model outputs available for the U.S. Pacific Islands region shows a range of possible future precipitation changes, with implications for economic and policy choices. In Hawaiʻi, end-of-century rainfall projections under a higher scenario (RCP8.5) range from small increases to increases of to up to 30% in wet areas, and from small decreases to decreases of up to 60% in dry areas.[34,35]

Using global climate model results for the lower scenario (RCP4.5) (see the Scenario Products section of App. 3), rainfall in Micronesia is projected to become as much as 10% lower to as much as 20% higher than at present within the next several decades, changes that are within the range of natural variability.[63] Changes are projected to be slightly greater by the end of the century but still within the −10% to +20% range for Micronesia.[63] In American Sāmoa, rainfall is projected to increase by up to 10% by mid-century compared with the present, with additional slight increases by the end of the century.

While rainfall in Hawaiʻi generally has been decreasing, it is also becoming more extreme.[64,65] Both extreme heavy rainfall events (causing increased runoff, erosion, and flooding) and droughts (causing water shortages) have become more common.[66] The number of consecutive wet days and the number of consecutive dry days are both increasing in Hawaiʻi.[66] In American Sāmoa, drought magnitude and duration have minimal decreasing trends.[23]

Hawaiʻi Annual Average Temperature Changes

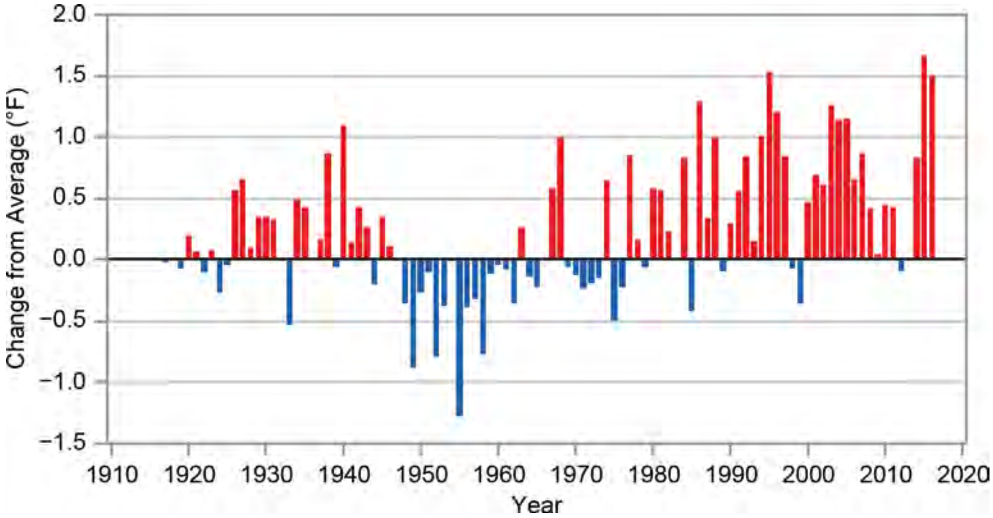


Figure 27.5: In Hawaiʻi, annual average temperatures over the past century show a statistically significant warming trend, although both warming and cooling periods occurred. Based on a representative network of weather stations throughout the islands, this figure shows the difference in annual average temperature as compared to the average during 1944–1980 (this period was selected as the baseline because it has the greatest number of index stations available), with red bars showing years with above average temperatures and blue bars showing years with below average temperatures. As temperature continues to rise across the region and cloud cover decreases in some areas, evaporation is expected to increase, causing both reduced water supply and higher water demand. Source: University of Hawaiʻi at Mānoa, Department of Geography and Environment.

Hawaiʻi Rainfall Trends

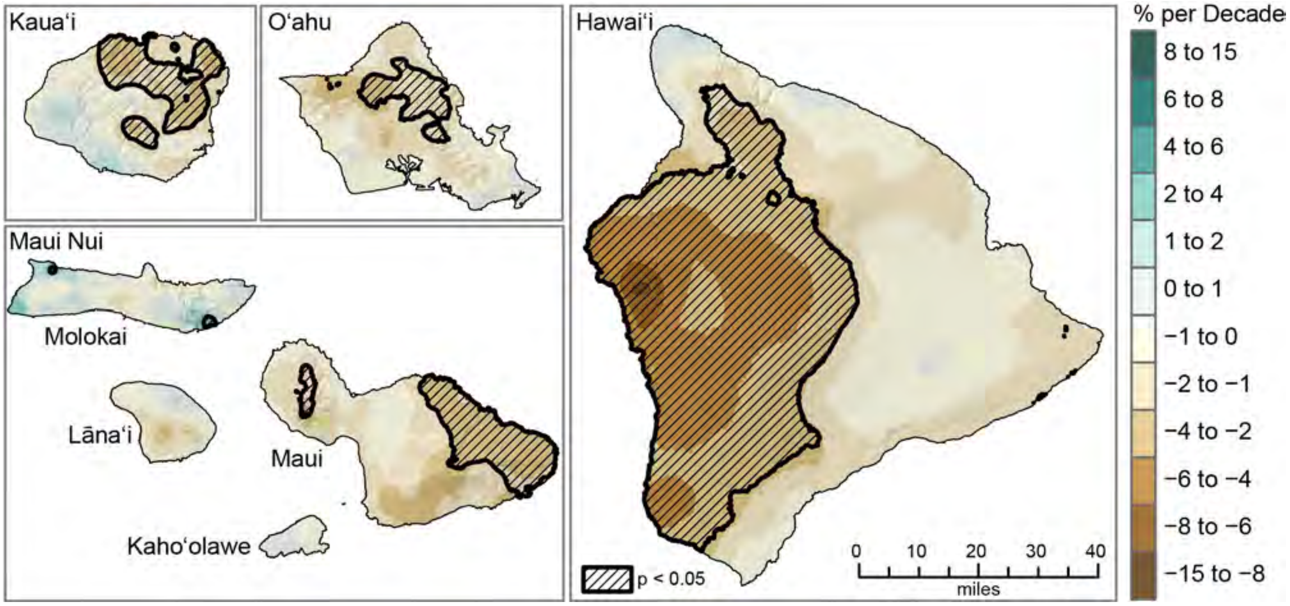


Figure 27.6: The figure shows the changes in annual rainfall (percent per decade) from 1920 to 2012 for the State of Hawaiʻi. Statistically significant trends are indicated with black hatching. Almost the entire state has seen rainfall decreases since 1920. The sharpest downward trends are found on the western part of Hawaiʻi Island. On other islands, significant decreases have occurred in the wetter areas. Source: adapted from Frazier & Giambelluca 2017.[60] © Royal Meteorological Society.

Higher rates of evaporation can strongly affect water resources by reducing the amount of water available (water supply) and by increasing the amount of water needed for irrigation and outdoor residential uses (water demand). Increasing temperatures throughout the Hawai'i–USAPI region and decreased cloud cover in some areas will cause increases in rates of evaporation. These increases will worsen effects of reduced rainfall by further reducing water supply and simultaneously increasing water demand.

Streamflow in Hawai'i has declined over approximately the past 100 years, consistent with observed decreases in rainfall.[6] Trends showing low flows becoming lower indicate declining groundwater levels. On islands such as O'ahu, water supply is mainly derived from groundwater.[67] If these declines continue due to further reductions in rainfall and/or increases in evaporation, groundwater availability will be impaired. Chronic water shortages are possible as rainfall decreases and both evaporation and the water requirements of a growing human population increase.

Given the small land areas and isolation of islands, and the current high level of year-to-year climate variability, even small changes in average climate are likely to cause extreme hardship. In the USAPI, subsistence-based agriculture persists, but the cultural and economic conditions that provided resilience have been eroded by the effects of colonization and globalization.[68] Hence, especially severe impacts of climate shifts are expected in these communities. Decreases in precipitation, together with saltwater contamination of groundwater systems due to sea level rise, threaten water and food security in some locations.[18,69,70]

Adaptation. Impacts and risks from climate change will vary due to differences in hydrological characteristics and the governance and adaptive capacity of each island. To address ongoing and future impacts of these changes, adaptive capacity can be enhanced by enabling individual island communities to identify and prioritize climate-related risks.[71] In Hawai'i, adaptation to address water shortages is already taking place through successful water conservation programs (see Case Study "Planning for Climate Impacts on Infrastructure"), watershed protection (Watershed Partnerships), drought planning (Commission on Water Resource Management), and changes in plumbing codes and policies (Fresh Water Initiative) to enhance groundwater recharge and wastewater reuse.[72,73]

In the USAPI, potential adaptation measures include development or improvement of emergency water shortage planning, including portable desalination systems and rapid-response drinking water shipments, although the high costs would prohibit larger desalination plants on most islands and atolls without international aid or other finance mechanisms.[74,75] Island communities can also improve their resilience to water shortages by increasing both rooftop water catchment and storage system capacity and by adopting drought-resistant and salt-tolerant crop varieties.

Throughout the region, the number of climate and water resources monitoring stations has declined,[23,76,77] reducing the ability of researchers to project future changes in climate. Restoring and enhancing monitoring of rainfall, evaporation-related climate variables (net radiation, air temperature, humidity, and wind speed), soil moisture, streamflow, and groundwater levels—critically important information for understanding, planning, and assessing adaptation actions—are prerequisites to building adaptive capacity to address the impacts of climate change on water resources.

Case Study: Planning for Climate Impacts on Infrastructure with the Honolulu Board of Water Supply (BWS)

The City and County of Honolulu Board of Water Supply (BWS) serves approximately one million customers on the island of O‘ahu, Hawai‘i, with about 145 million gallons per day (mgd) of potable (drinkable) groundwater and 10 mgd of nonpotable water.[78] The municipal system supports a large urban center, but the infrastructure is deteriorating.[78] Following the release of the 2012 Pacific Islands Regional Climate Assessment,[23] the BWS was concerned that changing climate patterns would affect both the quality and quantity of the water supply. Available projections showed increasing air temperature and drought risk,[23,34,35,36,60] reduced aquifer recharge, and coastal erosion that will impact wells and infrastructure.[41]

To proactively increase their capacity to respond and adapt to impacts of climate variability and change, the BWS was already implementing holistic long-term strategies to increase supply and lessen demand, including watershed management, groundwater protection, and a water conservation program. Because of these strategies, from 1990 to 2010, per capita use decreased from 188 to 155 mgd. However, total demand is still projected to increase 5% to 15% by 2040 due in part to population growth, with the most increases in areas of existing high population density.[78]

In 2015, the BWS partnered with researchers and consultants to assess projected climate change impacts on their infrastructure and to identify vulnerabilities over the next 20 to 70 years using a scenario planning approach to consider a range of plausible future climate and socioeconomic conditions. The vulnerability assessment considers extreme heat, coastal erosion, flooding (from wave overwash, sunny-day groundwater rise, and storms), annual and seasonal drought patterns, and changes in groundwater recharge impacts. As a project outcome, the BWS will develop a prioritized set of adaptive actions to minimize the range of climate impacts, including urgent capital improvements and updates to engineering standards.[79]

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism. Terrestrial habitats and the goods and services they provide are threatened by rising temperatures, changes in rainfall, increased storminess, and land-use change. These changes promote the spread of invasive species and reduce the ability of habitats to support protected species and sustain human communities. Some species are expected to become extinct and others to decline to the point of requiring protection and costly management.

Island landscapes and climates differ dramatically over short distances, producing a wide variety of ecological habitats and profoundly influencing the abundance and distribution of organisms, many of which have evolved to live in very specific environments and in close association with other species. Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function (see Ch. 7: Ecosystems, KM 1).

The Hawaiian Islands illustrate the challenges the broader Pacific region is facing. Ninety percent of the terrestrial species native to Hawai‘i are endemic (unique to the region). New, and potentially invasive, species are arriving much more frequently than in the past.[80,81] Hawai‘i is home to 31% of the Nation’s plants and animals listed as threatened or endangered, and less than half of the landscape on the islands is still dominated by native plants.[82] A similar picture describes most of the USAPI, as well. For example, Guam is well known for the decimation of its birds by the accidental introduction of the brown tree snake.

Nesting seabirds, turtles and seals, and coastal plants in low-lying areas are expected to experience some of the most severe impacts of sea level rise.[83] As detailed in the following section, rising sea levels will both directly inundate areas near shorelines and cause low-lying areas to flood due to the upward displacement of shallow aquifers. Rising sea levels also increase the tendency of large waves to wash inland and flood areas with saltwater, making the soil unsuitable for many plants and contaminating the underlying aquifer so that the water is not fit for drinking or crop irrigation.

Atolls are projected to be inundated, impacting existing on-island ecosystems.[18] Atoll communities that depend on subsistence agriculture already experience loss of arable land for food crops such as taro and breadfruit,[70] along with the degradation of aquifers from sea level variability and extreme weather. Without dramatic adaptation steps, the challenges of sea level rise will likely make it impossible for some atolls to support permanent human residence. Wildlife that relies on coastal habitats will likely also be severely impacted. More than half of the global populations of several seabird species nest in the atolls and low islands of Northwestern Hawaiian Islands. In addition to the direct impact from the loss and degradation of habitat, Key Message 4 describes how these species are at risk from changes in prey availability and increasing land surface temperatures.[84]

On many Pacific islands, native mangroves are highly productive coastal resources that provide a number of ecosystem services, including storm protection and food and building materials for Indigenous and local communities. Mangroves also serve as fish nursery areas, trap land-based sediment that would otherwise flow to coral reefs,[85] and provide habitat for many species. They are important reservoirs of organic carbon, providing yet another ecosystem service.[86] Mangroves are already under threat from coastal development and logging. Climate change, particularly sea level rise, will likely add additional stress.[87,88]

The planning and economic implications for biodiversity management are substantial. The main islands of Hawaiʻi have more than 1,000 native plant species,[89] and many of these are vulnerable to future climate shifts. Projections under a higher scenario (RCP 8.5) suggest that by the end of the century, the current distributions of more than 350 native species will no longer be in their optimal growing climate range.[90] For example, 18 of 29 native species studied within Hawaiʻi Volcanoes National Park are projected to shrink in range, such that most of the high-priority areas managed to protect biodiversity are projected to lose a majority of the studied native species.[91] Approximately $2 million is spent annually to manage these areas (dollar year not reported),[92] so climate-driven changes in plant distribution would have significant consequences on the allocation of funds. A global analysis suggests that the displacement of native species would provide increased opportunities for the establishment and spread of invasive species and that biodiversity would decrease as a result.[93,94]

Throughout the Pacific, climate change will likely alter ecosystem services provided by agroforestry (the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits). In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, upland or inland forest services include substantial acreage in mixed agroforests (forests with various trees, lower shrubs, and row crops used for food, building, and cultural practices).[95,96] Agroforest production is impacted by drought, flooding, soil and water salinization (increased salt content in low-lying areas), wind, disease, pests, and clearing for development.[70] Climate change is projected to exacerbate these impacts in complex patterns related to the stressors present in specific locations.

Increases in air temperature are projected to have severe negative impacts on the range of Hawaiian forest birds. Avian malaria currently threatens this iconic fauna except at high elevations, where lower temperatures prevent its spread. However, as temperatures rise, these high-elevation sites will become more suitable for malaria. Model projections suggest that even under moderate warming, 10 of 21 existing forest bird species across the state will lose more than 50% of their range by 2100 (Figure 27.7). Of those, 3 are expected to lose their entire ranges and 3 others are expected to lose more than 90% of their ranges,[43,97] making them of high concern for extinction.

Hawaiian Forest Bird Species

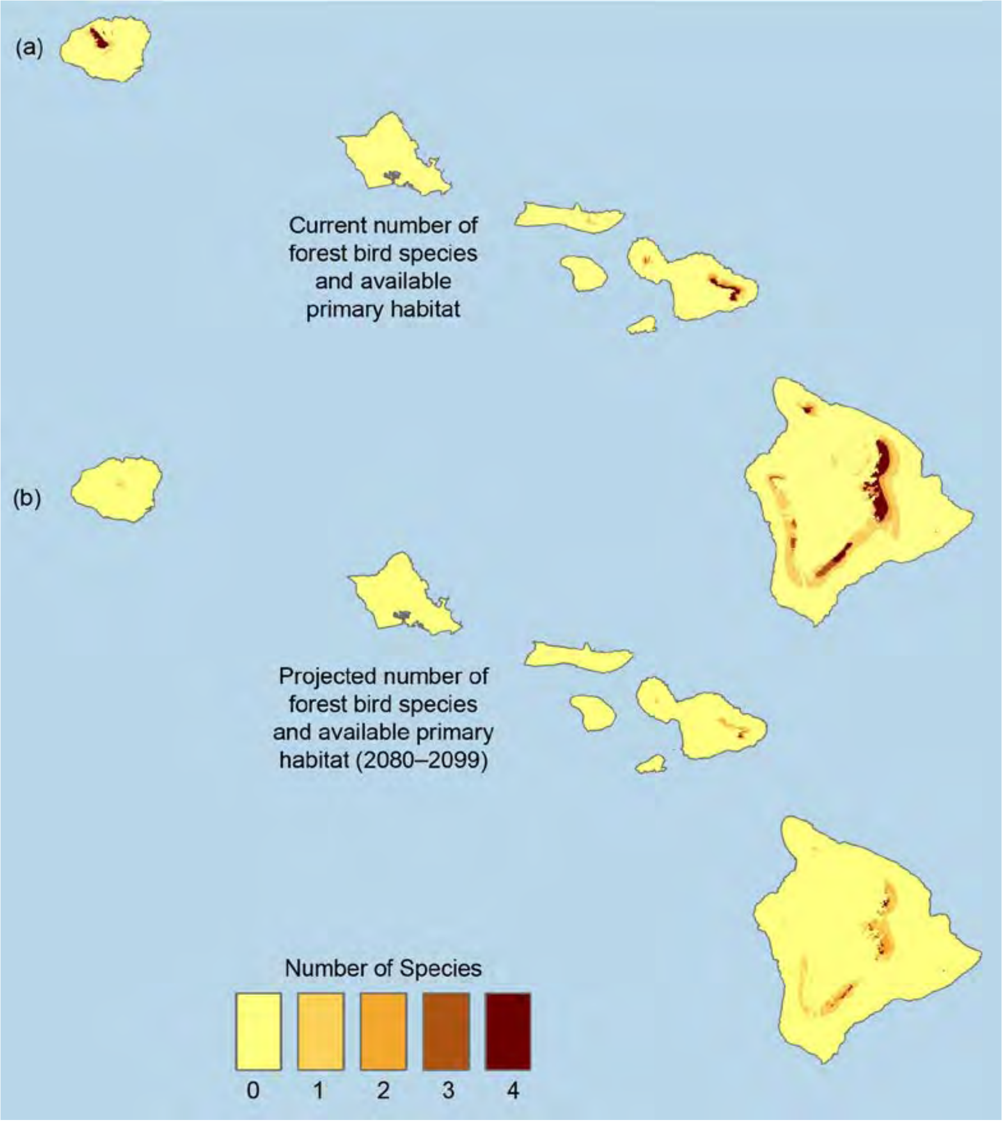


Figure 27.7: The figure shows the number of native Hawaiian forest bird species based on model results for (a) current and (b) future climate conditions. The future conditions are for the year 2100 using the middle-of-the-road scenario (SRES A1B). These projections include 10 species that represent the most rare and endangered native forest birds in Hawai‘i. The number of these species and their available habitat are projected to be drastically reduced by 2100. Sources: adapted from Fortini et al. 2015[43] (CC BY 4.0).

Streams on U.S. Pacific Islands are also home to native fauna that are unique and typically restricted to specific island groups such as the Mariana, Sāmoan, and Hawaiian archipelagos. A model of streamflow and habitat on the Island of Maui suggests that physical habitat for stream animals will decrease by as much as 26% in some streams under a higher scenario (RCP8.5), but the overall forecast is for habitat changes of less than 5% by 2100.[98] Throughout Hawaiʻi, elevated stream water temperatures from urbanization and a warming climate will likely reduce available habitat for temperature-sensitive species. Additionally, the larvae of native Hawaiian stream animals develop in the ocean, and exposure to ocean acidification puts them at risk of physiochemical changes resulting in lower reproductive success.[99]

Adaptation. Adapting to the impacts of climate change on terrestrial ecosystems is challenging. Management measures can take years to design and fund. Currently, understanding specific impacts of climate change on a particular ecosystem is confounded by other stressors (such as land development and invasive species) and clouded by a lack of precision in forecasting how sea level, rainfall, and air temperatures will change at the ecosystem or habitat level. A recent report summarizes both vulnerabilities and potential adaptations across all Hawaiian Islands and ecosystem types.[100] Through research and collaboration with Indigenous communities and land managers, ecosystem resilience to climate change can be enhanced and the most severe climate change effects on biodiversity decreased.[101] Many Pacific island communities view the protection and management of native biodiversity as ways to reduce climate change impacts. For example, a watershed model of the windward side of Hawaiʻi Island suggested that control of an invasive tree with high water demand would partially offset decreases in streamflow that might be caused by a drier climate.[44] In another example, resource managers are now keenly aware that climate change represents a serious long-term threat to Hawaiian forest birds. As a result, discussions involving multiple federal, state, and nongovernmental organization stakeholders are underway regarding a range of management responses, such as shifting protected areas, landscape-level control of avian malaria, and captive breeding and propagation. Some of these discussions are focused on adaptation to many aspects of climate change, whereas others address the broad range of threats to Hawaiian forest birds. Preparedness and planning can strengthen the resilience of native species and ecosystems to drought, wildfire, and storm damage, which will help them to avoid extinction due to climate change.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economies, housing and energy, transportation, and other forms of infrastructure. By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands. This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience. As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

The rate of global average sea level rise has accelerated[102,103] and has become very damaging in the region (Figure 27.8). Impacts include coastal erosion,[7,8] episodic flooding,[9,10] permanent inundation,[11] heightened exposure to marine hazards,[12] and saltwater intrusion to surface water and groundwater systems.[13,14] Already apparent on many shorelines, these problems endanger human communities by negatively impacting basic societal needs, such as food and freshwater availability, housing, energy and transportation infrastructure, and access to government services.[104]

Sea level could rise by as much as 1 foot by 2050 and by as much as 4 feet by 2100. Emerging science suggests that, for the Extreme sea level rise scenario, sea level rise of more than 8 feet by 2100 is physically possible. It is extremely likely that sea level rise will continue beyond 2100.[17,105]

Communities in Hawai‘i and the USAPI typically live in low-lying settings clustered around the coastal zone. Whether on high volcanic islands or low reef islands (atolls), exposure to marine hazards and dependency on global trade mean escalating vulnerability to climate change (Ch. 16: International, KM 1).[18]

Roadways Flood Periodically on O‘ahu

Figure 27.8: The photo shows North Shore, O‘ahu, in the winter of 2016. Episodic flooding in the Pacific Islands will increase as sea level rises. Photo credit: Steven Businger.

Until recently, global sea level rise of about 3 feet by the end of the century was considered a worst-case scenario, becoming more likely without reductions in global greenhouse gas emissions.[106] However, new understanding about melting in Antarctica,[107,108,109] Greenland,[110] and alpine ice systems;[111] the rate of ocean heating;[112,113] and historical sea level trends[103] indicates that it is physically possible to see more than double this amount this century (see Ch. 2: Climate, KM 4).[17,114]

The Intermediate sea level rise scenario predicts up to 3.2 feet of global sea level rise by 2100; however, recent observations and projections suggest that this magnitude of sea level rise is possible as early as 2060 in a worst-case scenario.[17] Studies in Hawai‘i show that the value of all structures and land projected to be flooded by 3.2 feet of sea level rise amounts to more than $19 billion (in 2013 dollars; $19.6 billion in 2015 dollars) statewide (Figure 27.9).[42] Across the state, nearly 550 Hawaiian cultural sites would be flooded or eroded, 38 miles of major roads would be chronically flooded, and more than 6,500 structures and 25,800 acres of land located near the shoreline would be unusable or lost, resulting in approximately 20,000 displaced residents in need of homes.[42]

Potential Economic Loss from Sea Level Rise, O‘ahu, Hawai‘i

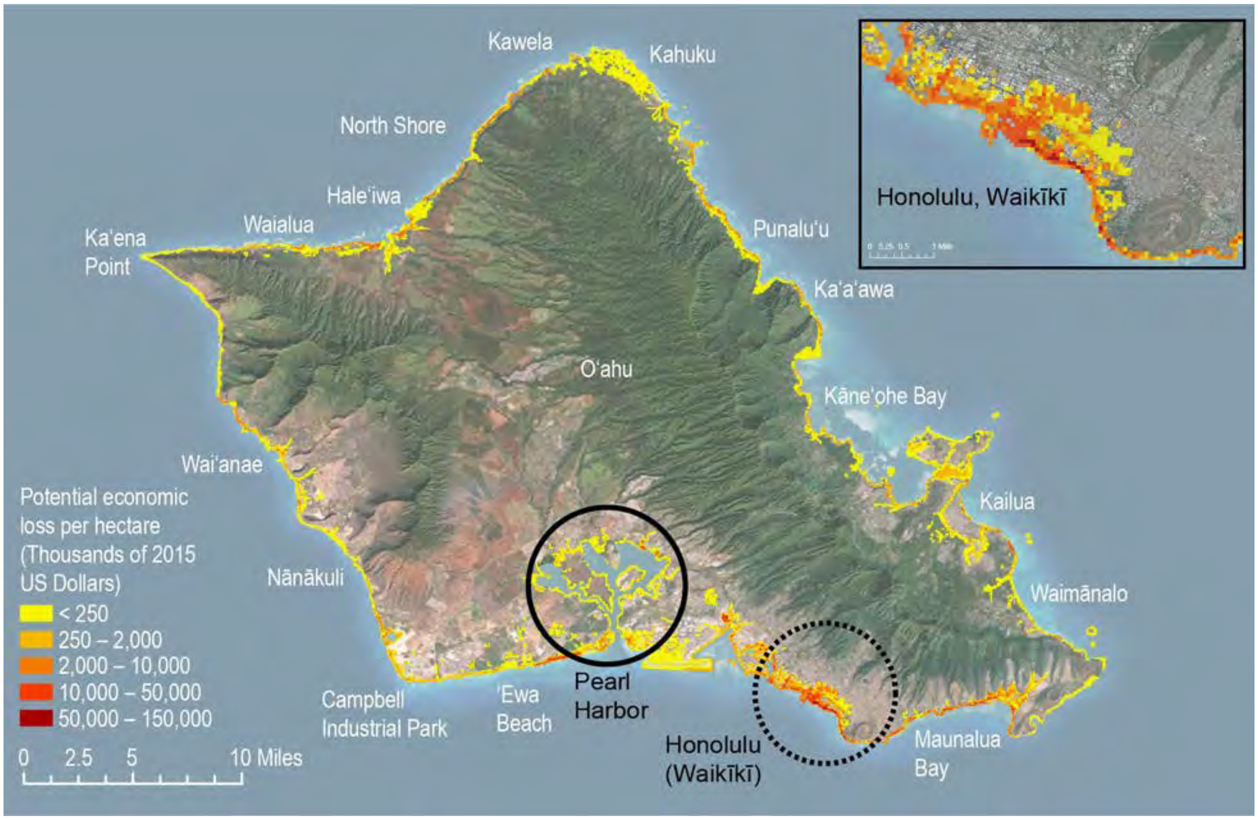


Figure 27.9: This map highlights potential economic losses (in 2015 dollars) in the exposure area associated with 3.2 feet of sea level rise on the island of O‘ahu, Hawai‘i. Potential economic losses are estimated from impacts to land and residential and commercial infrastructure. Highly impacted areas at risk of large economic losses include the U.S. Pacific Command and military infrastructure concentrated in Pearl Harbor (black circle) and the vulnerable tourist areas surrounding Waikīkī (dashed black circle). Source: adapted by Tetra Tech Inc. from the Hawai‘i Climate Change Mitigation and Adaptation Commission 2017.[42]

Owing to global gravitational effects, sea level rise will disproportionately affect the tropical Pacific[15] and potentially exceed the global average.[16] This, plus sea level variability internal to the Pacific Basin (see Figure 27.3), means that parts of the region are likely to experience the highest rates of sea level rise on the planet.[115] Scientific understanding of the timing and magnitude of future global sea level rise continues to improve,[116,117] making regular updates of management plans and engineering codes an important activity for island communities.

Because of accelerating sea level rise, coastal communities are projected to experience saltwater intrusion of aquifers and agricultural resources. As sea level rise continues in coming decades, freshwater sources will become increasingly at risk in communities dependent on restricted groundwater supplies.[69] Saltwater intrusion, which is amplified by climate variability and changing precipitation patterns (see Key Message 1),[12] is difficult to prevent, and, once damaged, water and food resources are challenging to restore.[13]

Future changes in global and regional precipitation vary among current climate models,[34,35,118] but the potential for changes in precipitation and the projected impacts of saltwater intrusion cast uncertainty over the sustainability of freshwater resources throughout the region. Because many island groups are very isolated, severe drought punctuated by saltwater intrusion can displace communities and produce feedback effects, such as failure of cultural, health, education, and economic systems (Ch. 17: Complex Systems).[119] However, strategic planning for the inevitability of these events can greatly reduce their impact.

In many areas, Pacific island coastal populations already exist on the edge of sustainability. Urban areas typically cluster around port facilities, as nearly all Pacific communities are tied to goods and services delivered by cargo ships. As the world’s most isolated chain of islands, Hawai‘i imports nearly 90% of its food at a cost of more than $3 billion per year (in 2004–2005 dollars),[120] resulting in government programs focused on food security.[121] Without adaptation measures, the additional stress on sustainable practices related to sea level rise is likely to drive islanders to leave the region and make new homes in less threatened locations (see Key Message 6 and Case Study “Bridging Climate Science and Traditional Culture”).[122]

Away from urban areas, many island communities rely on food gathered from the ocean and land. Populations on remote reef islands throughout Micronesia depend on water, food, and medical assistance that are often in question and are a source of persistent community stress. Extreme water levels accompanied by high waves have swept over remote atoll communities and destroyed taro patches, contaminated fragile aquifer systems, and deeply eroded island shores.[9,10,58]

In 2007, extreme tides coupled with high waves flooded the Federated States of Micronesia and triggered a national emergency. Food, water, and medical supplies had to be immediately delivered to dozens of communities in widely distributed locations to prevent famine (see Key Message 1) (see also Ch. 14: Human Health, KM 1).[57] It is likely that events of this type will increase in frequency as sea level rise accelerates in the future.

Rising sea surface temperatures are shifting the location of fisheries (Ch. 9: Oceans, KM 2).[123] Ocean warming [124] and acidification,[125,126] coupled with damaging watershed[127] and reef practices,[128] converge on island shores to increasingly limit the food resources that can be gathered from the sea (see Key Message 4).[129] Growing exposure to coastal hazards, such as storm surges,[130] compounds this threat to sustainability.

The Pacific Ocean is highly variable; fundamental characteristics of ENSO (see Box 27.1) appear to be changing.[131] Both El Niño and La Niña episodes are projected to increase in frequency and magnitude as the world warms.[3,52] Patterns of variability are complex,[132,133] and as climate changes over the long term, the oceanic and atmospheric forces that cause shorter-term climate variability (such as ENSO) also will be changing. Model projections indicate changing future wave conditions that will vary in complex ways spatially, by season, and with shoreline exposure and orientation.[37,38,134] These changes will challenge community efforts to define adaptation plans and policies.

The 2015–2016 El Niño was a Pacific-wide event with widespread impacts.[135] As warm water shifted from west to east, Palau, Yap, and other western Pacific communities experienced deep drought, requiring water rationing, as well as falling sea level that exposed shallow coral reefs.[136] In the central Pacific, Hawaiʻi experienced 11 days of record-setting rainfall that produced severe urban flooding,[137] while American Sāmoa faced long-term dry conditions punctuated by episodic rain events. Honolulu experienced 24 days of record-setting heat that compelled the local energy utility to issue emergency public service announcements to curtail escalating air conditioning use that threatened the electrical grid (Ch. 4: Energy, KM 1).[138] Nine months of drought stressed local food production, and a record tropical cyclone season saw Hawaiʻi monitoring three simultaneous hurricanes at one point.[139]

There is great uncertainty about how Pacific variability occurring on shorter timescales (for example, El Niño and La Niña) will combine with multidecadal changes in temperature, waves, rainfall, and other physical factors. This variability affects sea level extremes, which are likely to become more frequent this century,[4,12] along with changes in precipitation,[140] ocean temperature,[113] and winds.[141] These, in turn, drive difficult-to-forecast stressors that challenge the sustainability of coastal communities.

To date, tropical cyclone frequency and intensity have not been observed to change in the region of the USAPI. Trade winds and monsoon wind characteristics are expected to change in the future, but projections for specific geographic locations are unclear.[142] Under scenarios with more warming (for example, SRES A1B),[143] wind speeds are projected to decrease in the western Pacific and increase in the South Pacific;[142] central Pacific tropical cyclone frequency and intensity are expected to increase;[40,142] and in the western and South Pacific, tropical cyclone frequency is projected to decrease, while cyclone intensity is projected to increase.[142] Combined with continued accelerations in sea level rise, storm surge associated with a tropical cyclone has the potential to deliver a profound shock to a community beyond any ability to meaningfully recover.

Adaptation. Despite these threats, many Pacific communities are growing more resilient with renewed focus on conservation,[144] sustainably managing natural resources,[145] adapting to climate change,[146] and building more resilient systems.[147] Pacific island governments are taking steps to anticipate marine flooding (securing food and water resources) and doing so in the context of environmental conservation. Islanders throughout the USAPI are committing to demonstrate climate leadership, identifying sector vulnerabilities, and calling on their international partners to support their implementation of climate change resilience and adaptation actions.[55,148,149,150,151,152]

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat. Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5).

The ocean around Hawai‘i and the USAPI supports highly diverse marine ecosystems that provide critical ecosystem services.[123] Coral reef ecosystems are vitally important for local subsistence, tourism, and coastal protection. The pelagic (open ocean) ecosystem supports protected species, including sea turtles, sea birds, and marine mammals, as well as economically valuable fisheries for tunas and other pelagic fishes. In Hawai‘i, for example, coral reefs inject an estimated $364 million in goods and services annually (in 2001 dollars) into the local economy,[19] while the landings from the pelagic longline fisheries are worth over $100 million annually (in 2012–2013 dollars).[153]

Climate change is already being observed in the Pacific Ocean. Sea surface temperatures and ocean pH, an indicator of acidity, are now beyond levels seen in the instrument record.[154] Additionally, oxygen levels in the subtropical Pacific have been declining over the past five decades, negatively impacting fishes that draw oxygen from the water.[155] Impacts from sea level rise on coastal habitats and infrastructure have already occurred in the region, and the rate of sea level rise is projected to accelerate (see Key Message 3).

Widespread coral bleaching and mortality occurred during the summers of 2014 and 2015 in Hawai‘i and during 2013, 2014, and 2016 in Guam and the Commonwealth of the Northern Mariana Islands. Impacts varied by location and species, but the 2015 bleaching event resulted in an average mortality of 50% of the coral cover in western Hawai‘i.[45] Coral losses exceeded 90% at the remote and pristine equatorial reef of Jarvis Island.[156]In response to the prolonged and widespread bleaching, the State of Hawai‘i convened an expert working group to generate management recommendations to promote reef recovery.[157]

Under projected warming of approximately 0.5°F per decade, coral reefs will experience annual bleaching beginning in about 2035 in the Mariana Archipelago, in about 2040 in American Sāmoa and the Hawaiian Islands, and in about 2045 at other equatorial reefs (Figure 27.10).[46] Warming reductions on the order of the aims of the 2015 Paris Agreement are projected to delay the onset of annual severe bleaching by 11 years on average.[46] Because some coral species are more resilient to thermal stress than others, low levels of thermal stress are expected to only alter the types of corals present. However, at high levels of thermal stress, most coral species experience some bleaching and mortality.[158] Ocean acidification reduces the ability of corals to build and maintain reefs,[125,159] while land-based nutrient input can substantially exacerbate acidification and reef erosion.[160] Under the higher scenario (RCP8.5), by the end of the century, virtually all coral reefs are projected to experience an ocean acidification level that will severely compromise their ability to grow.[125,161] Loss of coral reef structure results in a decline in fish abundance and biodiversity, negatively impacting tourism, fisheries, and coastal protection.[123] In the Hawaiian Archipelago under the higher scenario (RCP8.5), coral reef cover is projected to decline from the present level of 38% to 11% in 2050 and to less than 1% by the end of the century. This coral reef loss is projected to result in a total economic loss of $1.3 billion per year in 2050 (in 2015 dollars, undiscounted) and $1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, the lower scenario (RCP4.5) would avoid 16% of coral cover loss and $470 million in damages per year (in 2015 dollars, undiscounted) compared to the higher scenario (RCP8.5).[162] In the central and western Pacific, coral reef cover is projected to decline by 2050 from a present-day average of 40% to 10%–20%, and coral reef fish production is expected to decline by 20% under a high emissions scenario (SRES A2).[123] Declines in maximum catch potential exceeding 50% from late-20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones (EEZs) of most islands in the central and western Pacific.[163] A key uncertainty is the extent to which corals can develop resilience to the rapidly changing ocean conditions.[164,165] Changing ocean temperature and acidification will impact many other organisms that will likely alter the functioning of marine ecosystems.

Projected Onset of Annual Severe Coral Reef Bleaching

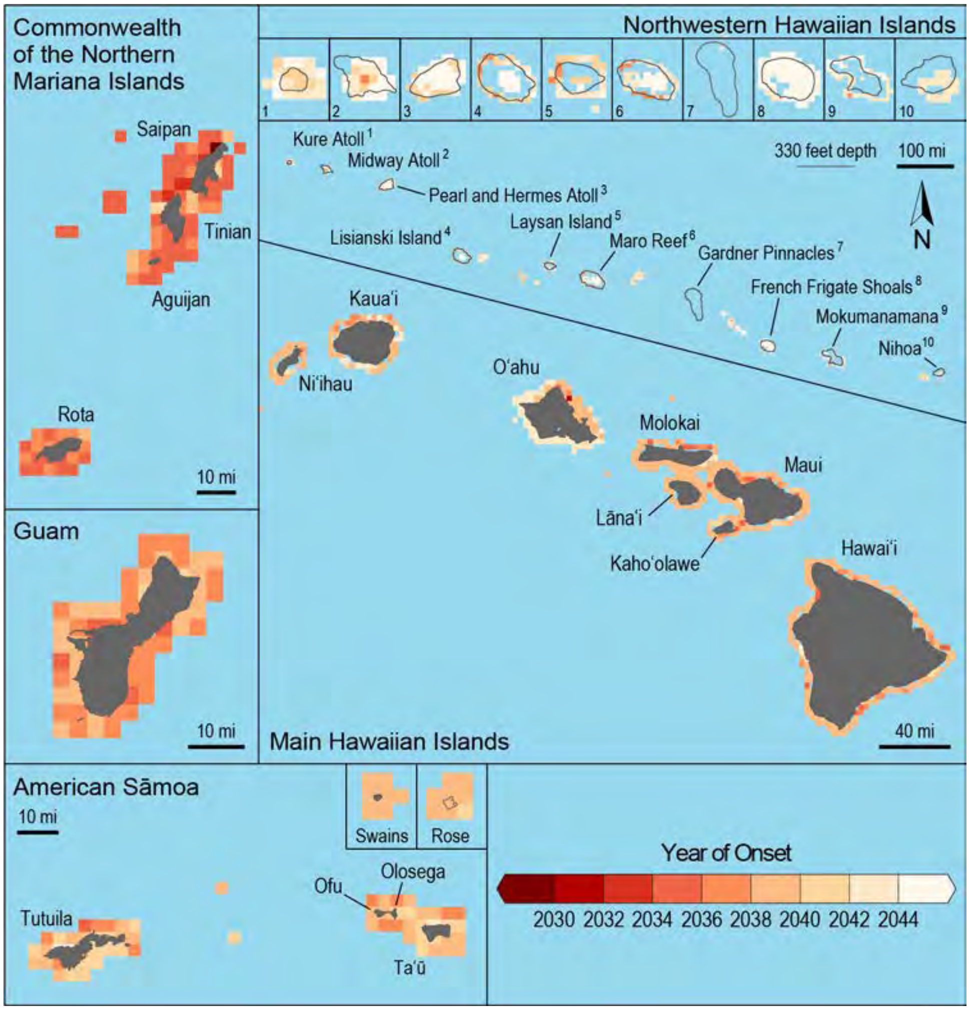


Figure 27.10: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. Source: NOAA.

Mangroves provide coastal protection and nursery habitat for fishes and, in some cases, protect coral reefs from sediment and enhance the density of coral reef fishes.[166] Sea level rise has caused the loss of mangrove areas at sites in American Sāmoa[87] and is projected to further reduce mangrove area in the Pacific Islands region by 2100.[87,88]

In the open ocean, warming is projected to reduce the mixing of deep nutrients into the surface zone. Under the higher scenario (RCP8.5), increasing temperatures and declining nutrients are projected to reduce tuna and billfish species' richness and abundance in the central and western Pacific Ocean, resulting in declines in maximum fisheries yields by 2%–5% per decade.[129,167,168,169] Climate change is also projected to result in overall smaller fish sizes, further adding to the fishing impact (Ch. 9: Oceans, KM 2).[170]

Tuna habitat in the equatorial region is projected to shift eastward with changing temperatures, so that by the end of the century the availability of skipjack tuna within the EEZs of Micronesian countries will likely be 10%–40% lower than current levels.[123]

On low-lying islands and atolls, sea level rise is projected to result in the loss of resting and nesting habitat for sea birds and sea turtles and the loss of beach and pupping habitat for Hawaiian monk seals. Modeling exercises that take wave height into account project much greater habitat flooding than sea level rise alone would suggest.[18,38,171] For example, sea level rise of about 6 feet combined with both storm wave run-up and concurrent groundwater rise is projected to wash out 60% of the albatross nests across the U.S. Marine National Monuments each breeding season.[83]

Adaptation. Management actions that remove other stressors on corals (such as those recommended in Hawai‘i, Guam, and the Commonwealth of the Northern Mariana Islands after the recent bleaching events) have been proposed as strategies to enhance the resilience of corals to moderate levels of thermal stress and to aid their recovery.[157] However, experience from the 2016 extreme bleaching on the Great Barrier Reef found that water quality and fishing pressure had minimal effect on the unprecedented bleaching, suggesting that local reef protection measures afford little or no defense against extreme heat.[158] This suggests that more active intervention is necessary, such as incorporating assisted evolution and selectively breeding corals, to enhance their resilience to rapidly rising ocean temperatures and acidification,[172] as is being tested in Hawai‘i. In the case of the pelagic ecosystem, fishing and climate change work together to reduce the abundance of tunas and billfishes targeted by the fishery.[170,173] Thus, an ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.[20] Lastly, relocations of seabirds to nesting sites on higher islands have been proposed to mitigate lost nesting habitat on low-lying islands and atolls.[83]

Key Message 5

Indigenous Communities and Knowledge

Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources. Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Indigenous communities of the Pacific have an inseparable connection to and derive their sense of identity from the lands, territories, and resources of their islands. This connection is traditionally documented in genealogical chants and stories transmitted through oral history.[146] The rich cultural heritage of Pacific island communities comprises spiritual, relational, and ancestral interconnectedness with the environment[174] and provides land security, water and energy security, livelihood security, habitat security,[175] and cultural food security.[176] Climate change threatens this familial relationship with ancestral resources[177] and is disrupting the continuity that is required for the health and well-being of these communities (this experience is common to many tribal and Indigenous communities across the United States) (see Ch. 15: Tribes, KM 2).[176,177]

Sea level rise imperils Indigenous communities of the Pacific. The sea that surrounds Pacific island communities continues to rise at a rate faster than the global average,[115] with documented impacts on agriculture, coastal infrastructure, food security, livelihoods, and disaster management in the Republic of Palau[149] and the Republic of the Marshall Islands.[147]

In Hawai‘i, sea level rise impacts on traditional and customary practices (including fishpond maintenance, cultivation of salt, and gathering from the nearshore fisheries) have been observed (Figure 27.11).[177] Since 2014, Indigenous practitioners have had limited access to the land where salt is traditionally cultivated and harvested due to flooding and sea level rise. Detachment from traditional lands has a negative effect on the spiritual and mental health of the people (Ch. 14: Human Health, KM 1; Ch. 15 Tribes, KM 2).[176]

Salt Cultivation on Kaua‘i

Figure 27.11: Flooding on the island of Kaua‘i, Hawai‘i, impacts the cultural practice of pa‘akai (salt) cultivation. Photo credit: Malia Nobrega-Olivera.

Case Study: Bridging Climate Science and Traditional Culture

To identify adaptive management strategies for Molokai’s loko i‘a (fishponds) built in the 15th century, the nonprofit Ka Honua Momona’s fishpond restoration project gathered Hawai‘i’s climate scientists, Molokai’s traditional fishpond managers, and other resource managers to share knowledge from different knowledge systems (Figure 27.12). Loko i‘a are unique and efficient forms of aquaculture that cultivate pua (baby fish) and support the natural migration patterns over the life of the fish. The lens of the ahupua‘a (the watershed, extending from the uplands to the sea) was an important framework for this project. Sea level rise, surface water runoff, and saltwater intrusion into the freshwater springs are a few of the climate change impacts to which fishponds are vulnerable.[177] A key outcome of creating this collaborative model was strengthening relationships between diverse groups of people committed to responding to ecosystem changes and protecting cultural and natural resources.

Preparing Molokai’s Fishponds for Climate Change

Figure 27.12: Ka Honua Momona hosted Molokai’s loko i‘a managers, Hawai‘i’s climate scientists, and other resource managers in April 2015. Photo credit: Hau‘oli Waiau.

Ocean acidification and drought, in combination with pollution and development, are negatively affecting fisheries and ecosystems (which are drivers of tourism), directly impacting the livelihood security of Pacific communities. For example, across all Pacific island countries and territories, industrial tuna fisheries account for half of all exports, 25,000 jobs, and 11% of economic production.[178] In Hawai‘i, between 2011 and 2015, an annual average of 37,386 Native Hawaiians worked in tourism-intensive industries; based on the 2013 U.S. census, this number represents 12.5% of the Native Hawaiian population residing in Hawai‘i.

Climate change is impacting subsistence[18,70,95,123,175] and cultural food security[70,176] of Pacific island communities. Subsistence food security is essential for the survival of Indigenous peoples of the world and is valued socially, culturally, and spiritually.[175] Cultural food security refers to the provision of food that is a necessary part of a community's regular diet and sustains the connection with cultural and social practices and traditions.[176] Taro and fish are two examples of cultural foods important to the livelihoods of Pacific island communities and to economic development for the community and government.[123]

In Hawaiʻi, climate change impacts, such as reduced streamflow, sea level rise, saltwater intrusion, and long periods of drought, threaten the ongoing cultivation of taro and other traditional crops.[177] Identifying and developing climate-resilient taro and other crops are critical for their continued existence.[179] In Yap, taro is a key element of the diet. Groundwater salinization has resulted in smaller corms (underground tubers), causing declines in harvest yield.[180] In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, crops grown in mixed agroforests provide important sources of nutrition, meet subsistence needs, supplement household incomes through sales at local farmers' markets, and support commercial production.[95,96] These crops include breadfruit, mango, and coconut as overstory components; citrus, coffee, cacao, kava, and betel nut as perennial components; and banana, yams, and taro. Climate change is expected to result in changes in farming methods and cultivars (Figure 27.13). Consequently, these changes will likely impact the relationship between communities and the land. These kinds of climate impacts lead to an increased dependence on imported food that is of little nutritional value.[181] This is a public health concern for Hawaiʻi and the USAPI, as Indigenous Pacific Islanders have the highest rates of obesity and chronic diseases, such as diabetes, in the region.[182]

The rich body of traditional knowledge is place-based and localized[21] and is useful in adaptation because it builds on intergenerational sharing of observations[22] of changes in climate-related weather patterns, ocean phenomena, and phenology (the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life). These observations, gathered over millennia, are useful in defining baselines and informing adaptive strategies.[183] Indigenous cultures are resilient, and their resilience has empowered Pacific island communities to survive several millennia on islands.[180] These communities have survived extreme events and responded to change through adaptive mechanisms based on traditional knowledge that has evolved over many generations.[184]

Women play a vital role in ensuring that adaptation planning and action in the Pacific draw on traditional knowledge and new technologies.[184] The role of women in Indigenous communities includes maintaining crop diversity as collectors, savers, and managers of seeds and thus enhancing livelihood security for the community.[185] Indigenous women are also central in teaching, practicing, protecting, and transmitting traditional knowledge and practices.[185] Women have also been identified as a more vulnerable population to regional climate risks due to the role they have in terms of economic activities, safety, health, and their livelihoods.[147] For example, in Palau, as in the broader region, the central role of Indigenous women as lead project participants is key to the success of any project.

In Pacific island cultures, lunar calendars are tools used to identify baselines of an environment, track changes (kilo, in Hawaiian), and

Crop Trials of Salt-Tolerant Taro Varieties

Figure 27.13: Taro trials are underway in Palau, with results so far indicating that three varieties have tolerance to saltwater. Photo credit: Malia Nobrega-Olivera.

record seasonality, migration patterns, and weather.[183] In Hawai‘i, use of the traditional lunar calendar (kaulana mahina) and kilo in climate change adaptation assists communities with decision-making that allows for the best survival techniques.[183] In Mo‘omomi, Molokai, an intact coastal sand dune ecosystem in the main Hawaiian Islands, kaulana mahina has proven to be a useful tool that has enhanced the resilience of this coastline.[186,187] Similarly, a calendar for traditional Marshallese agroforestry crops recently was adapted to account for ENSO and climate conditions (see Figure 27.14).[188]

Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands, territories, and resources. Marine-managed areas, such as those designated under the Micronesia Challenge and the Papahānaumokuākea Marine National Monument in Hawai‘i, demonstrate a commitment by multiple partners to conserve marine resources. Over time, monitoring the ability of Indigenous peoples to continue to experience kinship and maintain traditional practices can help to preserve the cultural heritage associated with these protected areas. Documenting the kinds of governance structures or decision-making hierarchies created for their management can serve as a learning tool that can be shared with other island communities.

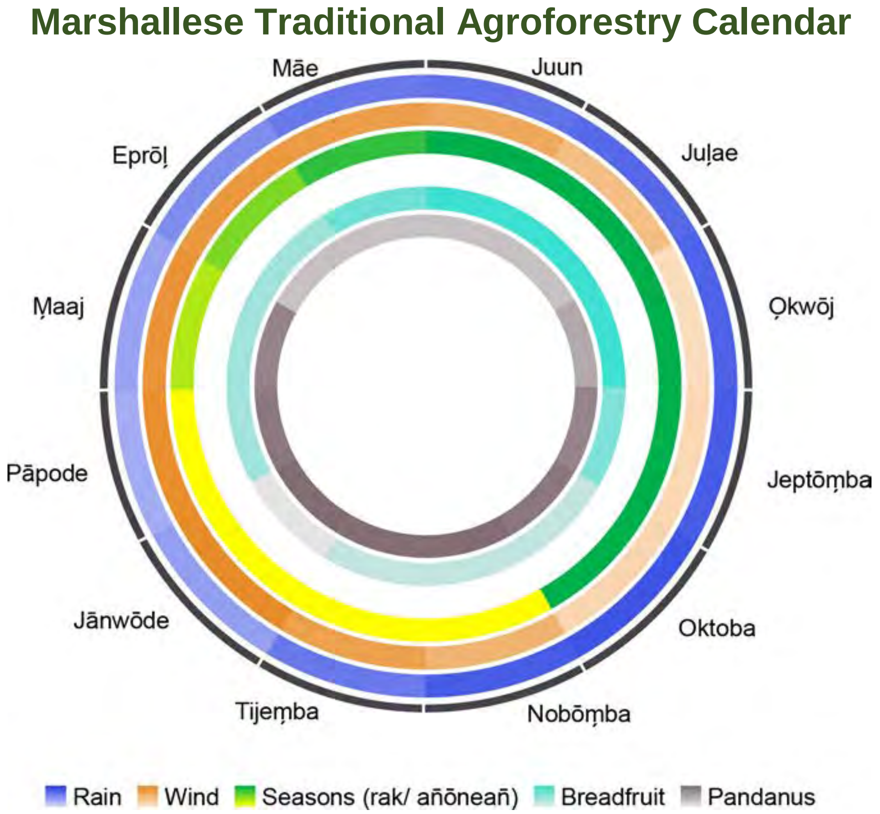


Figure 27.14: The Marshallese Traditional Agroforestry Calendar combines climate data and traditional season designations and knowledge about the harvest times of perennial crops throughout the year. Months are displayed in Marshallese on the outer ring, while inner rings show how wind and rain patterns and the harvest of two crops typically change throughout the year. The color gradients show the intensity of the harvest or the climate variable, with more intense colors representing larger amounts harvested or higher amounts of rain, for example, at various times. A web-based tool offers two versions, depending on the status of ENSO conditions. Source: adapted by Victor Garcia, Jr., from Friday et al. 2017.[188]

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs. In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation.

Sectoral impacts act together to compound environmental, social, cultural, and economic costs. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts. The interconnectedness of people in island communities and the interdependence between human activities and the natural environment[119] mean that extreme events cause multiple, layered impacts, intensifying their effects (see Ch.17: Complex Systems). While each of these impacts presents challenges, when combined, the environmental, social, cultural, and economic impacts will have compounding costs. In addition, as some types of extreme events become more frequent, recovery from those events will prove increasingly difficult for isolated, resource-challenged islands,[189] resulting in long-term declines in people's welfare.[190,191]

Coastal flooding is a widely recognized threat to low-lying areas (see Key Message 3).[7] Extreme sea level events—created by combinations of factors such as storm-generated waves, storm surges, king tides, and ENSO-related sea level changes (see Box 27.1), combined with ongoing sea level rise—pose multiple challenges to habitability; on atolls, they are a clear threat to communities' existence (Figures 27.15, 27.16, 27.17). In 2005, when Cyclone Percy hit the Northern Cook Islands, waves swept across the atoll from both the ocean and the lagoon sides. Fresh food supplies were destroyed due to saltwater intrusion into taro fields, 640 people were left homeless, and freshwater wells were polluted, posing a risk to public health. Saltwater contamination of the freshwater lenses lasted 11 months or longer.[13] In Tokelau, Cyclone Percy scattered human waste, trash, and other debris into the ocean and across the island. Tokelau's three atolls lost most of their staple crops, while fish habitats were destroyed.[192] The islands suffered beach erosion, and many live coral formations were covered by sand and debris. In addition, the storm damaged many of the hospitals, making treatment of the injured or displaced difficult.[193] Lack of technology and resources limits small islands' ability to adapt to these complex threats. The cascading effects on infrastructure, health, food security, and the environment result in significant economic costs.[194,195]

Sea level rise, the deterioration of coral reef and mangrove ecosystems (see Key Message 4), and the increased concentration of economic activity will make coastal areas more vulnerable to storms (see Key Message 3).[196] Pacific Islands already face underlying economic vulnerabilities and stresses caused by unsustainable development, such as the use of beaches for building materials that results in coastal erosion or the waste disposal on mangroves and reefs that undermines critical ecological functions. The compounding impacts of climate change put the long-term habitability of coral atolls at risk, introducing issues of sovereignty, human and national security,[197] and equity,[198,199,200] a subject of discussion at the international level.

An increase in the incidence of vector-borne diseases such as malaria and dengue in the Pacific Islands has been linked to climate variability and is expected to increase further as a result of climate change (see Ch. 14: Human Health, KM 1).[201,202] For example, in late 2013 and early 2014, Fiji experienced the largest outbreak of dengue in its history, with approximately 28,000 reported cases.[203]

Climate change impacts on ecological and social systems are already negatively affecting livelihoods[204,205,206] and undermining human security.[191,207] In some cases, changes in climate increase the risk of human conflict (see Ch. 16: International, KM 3).[191,207,208] However, exactly how and when these changes can lead to conflict needs further study.[208] Climate change poses a threat to human security through direct impacts on economies and livelihoods that aggravate the likelihood of conflict and risk social well-being.[209] For example, climate change puts ongoing disputes over freshwater in Hawaiʻi at risk of intensifying in the absence of policy tools to help resolve conflicts.[23] Human conflict in the Asia Pacific region is expected to increase as unequal resource distribution combines with climate impacts to affect communities that are heavily dependent on agriculture, forestry, and fishing industries.[210]

Flooding in Kosrae

Figure 27.15: A combination of heavy rain, exceptionally high tides, and waves caused flooding in Kosrae, the Federated States of Micronesia, in February 2017. Photo credit: Delia Sigrah.

Reservoirs in the Marshall Islands

Figure 27.16: A series of reservoirs that provide the main water supply on Majuro Atoll in the Republic of the Marshall Islands are filled with runoff from the Majuro airport runway. The water supply is vulnerable to drought and saltwater overwash from both the lagoon and ocean (pictured). Photo credit: Majuro Water and Sewer Company.

A Marshall Islands Storm

Figure 27.17: An unseasonable storm hit the Marshall Islands on July 3rd, 2015. Storms this strong historically have been rare in the Marshall Islands, but the frequency of the most intense of these storms is projected to increase in the western North Pacific in the future. Photo credit: Marshall Islands Journal.

Climate change is already contributing to migration of individuals and communities.[211,212] In March 2015, Marshall Islands Bikinian people gathered to discuss resettlement because of increased flooding from high tides and storms that was making the atoll of Kili uninhabitable (see Case Study "Understanding the Effect of Climate Change on the Migration of Marshallese Islanders").[213]

Climate change induced community relocation, a recognized adaptation measure, results in disruption to society–land relationships and loss of community identity.[214] Resettlement has resulted in people facing landlessness, homelessness, unemployment, social marginalization, food insecurity, and increased levels of disease.[122]

Inaction to address climate-related hazards is projected to lead to high economic costs that are preventable.[205] Remote island communities that are unprepared for extreme events would face disruptions of goods and services that threaten lives and livelihoods. Rebuilding is expensive and lengthy.[13,218,219,220] Further, due to the special connections Indigenous people have to ancestral lands and territories, any loss of these resources is a cultural loss (see Key Message 5).[221]

Case Study: Understanding the Effect of Climate Change on the Migration of Marshallese Islanders

As one of the lowest-lying island nation-states in the world, the Republic of the Marshall Islands (RMI) is acutely vulnerable to sea level rise, flooding, and the associated intrusion of saltwater into crucial freshwater supplies, traditional agriculture, and forestry. The number of Marshallese residing in the United States (excluding the U.S. Territories and Freely Associated States) has rapidly risen over the past decade, from 7,000 in 2000 to 22,000 in 2010,[215] which is equal to over 40% of RMI's current total population. There is also substantial internal migration, predominantly from outer islands to the main atoll of Majuro.[216,217] Whether migration is a potentially successful adaptation strategy is unknown. The factors triggering human migration are complex and often intertwined, making it difficult to pinpoint and address specific causes.

Decision-makers in both the RMI and the United States—for example, those who design policy related to immigrant access to services—need information to better understand the factors contributing to current migration and to anticipate possible future impacts of climate change on human migration. A current research project is studying the multiple reasons for Marshallese migration and its effects on migrants themselves and on the communities they are coming from and going to.

Early intervention, occurring already in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation (see Ch. 28: Adaptation, KM 4). Early intervention includes taking steps now to protect infrastructure, as is being done by the Honolulu Board of Water Supply (see Case Study "Planning for Climate Impacts on Infrastructure"), such as redesigning areas to allow for periodic inundation and flooding, reverting natural areas to facilitate a return to original drainage patterns, and building social networks to take immediate actions and plan future responses.[222] Policymakers prefer approaches that are low cost, yield benefits even in the absence of climate change, are reversible and flexible, and build safety margins into new investments to accommodate uncertain future changes.[196] Examples of safety margins include more climate-adapted housing, provisions to expand rainwater storage capacity in water tanks, reverse osmosis capabilities for removing salt from water (Figure 27.4), development of saline-tolerant crop varieties (Figure 27.13), and implementation of more effective early warning systems for typhoons, king tides, and coastal storms.

Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation, as well as other climate-related impacts. In some cases, the focus is on taking preventive measures to remove exposure to hazards, rather than focusing on protection and impact reduction (for example, through relocation or increased protection of threatened infrastructure). On Kosrae, the Federated States of Micronesia, for example, the Kosrae Island Resource Management Authority has laid out a strategy to redirect development inland (such as repositioning the main access road away from the shoreline to higher ground).[7]

Social cohesion is already strong in many communities in the region, making it possible to work together to take action. Stakeholders representing academia, resource managers, and government came together across the State of Hawai‘i to summarize ecosystem-specific vulnerabilities and prioritize potential adaptations at the island scale.[100] In Molokai, a community-led effort is underway to prepare traditional fishponds for climate change (see Case Study "Bridging Climate Science and Traditional Culture"). One of the core benefits of this effort is the strengthening of relationships between the diverse people who will benefit from collaborating to address future climate change impacts on the island.

Where successful, early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

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Traceable Accounts

To frame this chapter, the regional leads wanted to maximize inclusiveness and represent the key sectoral interests of communities and researchers. To select sectors and a full author team, the coordinating lead author and regional chapter lead author distributed an online Google survey from September to October 2016. The survey received 136 responses representing Hawaiʻi and all the U.S.-Affiliated Pacific Islands (USAPI) jurisdictions; respondents identified which of the National Climate Assessment (NCA) sectors they were most interested in learning about with respect to climate change in the Pacific Islands and suggested representative case studies.[223] The five top sectors were picked as the focus of the chapter, and a total of eight lead authors with expertise in those sectors were invited to join the regional team. To solicit additional participation from potential technical contributors across the region, two informational webinars spanning convenient time zones across the Pacific were held; 35 people joined in. The webinars outlined the NCA history and process, as well as past regional reports and ways to participate in this Fourth National Climate Assessment (NCA4).

A critical part of outlining the chapter and gathering literature published since the Third National Climate Assessment (NCA3)[224] was done by inviting technical experts in the key sectors to participate in a half-day workshop led by each of the lead authors. A larger workshop centered on adaptation best practices was convened with participants from all sectors, as well as regional decision-makers. In all, 75 participants, including some virtual attendees, took part in the sectoral workshops on March 6 and 13, 2017. Finally, to include public concerns and interests, two town hall discussion events on March 6 and April 19, 2017, were held in Honolulu, Hawaiʻi, and Tumon, Guam, respectively. Approximately 100 participants attended the town halls. Throughout the refining of the Key Messages and narrative sections, authors met weekly both via conference calls and in person to discuss the chapter and carefully review evidence and findings. Technical contributors were given multiple opportunities to respond to and edit sections. The process was coordinated by the regional chapter lead and coordinating lead authors, as well as the Pacific Islands sustained assessment specialist.

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures *(very high confidence)*, changing rainfall patterns *(low confidence)*, sea level rise *(very high confidence)*, and increased risk of extreme drought and flooding *(medium confidence)*. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls *(medium confidence)*. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

Description of evidence base

Vulnerability of water supplies to climate change: With their isolation and limited land areas, Hawaiʻi and the USAPI are vulnerable to the effects of climate change on water supplies.[72,225] Ongoing and projected changes in temperature and precipitation will have negative effects on water supplies in Hawaiʻi and some parts of the USAPI. For example, stream low flow and base flow in Hawaiʻi decreased significantly over the period 1913–2008, which is at least partly explained by a decline in precipitation.

Temperature change: In Hawaiʻi, air temperature increased by 0.76°F (0.42°C) over the past 100 years. The year 2015 was the warmest on record at 1.43°F (0.79°C) above the 100-year average. Mean and minimum (nighttime) temperatures both show long-term, statistically significant increasing trends, while the diurnal temperature range (the average difference between daily minimum and maximum temperature) shows a long-term, statistically significant decreasing trend.[59] Estimates of historical temperature changes in Hawaiʻi are based on the relatively few observing stations with long records and represent the best available data. Further temperature increases in the Hawaiʻi–USAPI region are highly likely. Northern tropical Pacific (including Micronesia) sea level air temperatures are expected to increase by 2.2°–2.7°F (1.2°–1.5°C) by mid-century and by 2.7°–5.9°F (1.5°–3.3°C) by 2100.[63] Southern tropical Pacific (including American Sāmoa) sea level air temperatures are expected to increase by 1.8°–3.1°F (1.0°–1.7°C) by mid-century and by 2.5°–5.8°F (1.4°–3.2°C) by 2100.[63] Increasing temperatures throughout the Hawaiʻi–USAPI region might cause increases in potential evapotranspiration,[226] with consequent negative impacts on water supplies.

Precipitation change: While Hawaiʻi precipitation has experienced upward and downward changes across a range of timescales, more than 90% of the state had a net downward rainfall trend during 1920–2012.[60] Projections of future precipitation changes in Hawaiʻi are still uncertain. Using a dynamical downscaling approach to project climate changes in Hawaiʻi for the 20-year period at the end of the this century under a middle-of-the-road scenario (SRES A1B) resulted in increases in mean annual rainfall of up to 30% in the wet windward areas of Hawaiʻi and Maui Islands and decreases of 40% in some of the dry leeward and high-elevation interior areas.[34] Somewhat different results were obtained using an independent statistical downscaling method.[34] For the lower scenario (RCP4.5), mean annual rainfall in Hawaiʻi is projected by statistical downscaling to have only small changes in windward areas of Hawaiʻi and Maui Islands, to decrease by 10%–20% in windward areas of the other islands, and to decrease by up to 60% in leeward areas for the period 2041–2070. For the same scenario, the late-century (2071–2100) projection is similar to the 2041–2070 projection, except that a larger portion of the leeward areas will experience reductions of 20%–60%. For the higher scenario (RCP8.5), windward areas of Hawaiʻi and Maui Islands will see changes between +10% and −10%, and rainfall in leeward areas will decrease by 10% to more than 60% by the 2041–2070 period. By the late-century period (2071–2100), windward areas of Hawaiʻi and Maui Islands will see increases of up to 20%, windward areas on other islands will have decreases of 10% to 30%, and leeward areas will have decreases of 10% to more than 60%. The number of climate and water resources monitoring stations has declined across the region,[23,76,77] reducing the ability of researchers to project future changes in climate.

Trends in hydrological extremes in Hawaiʻi: Increasing trends in extreme 30-day rainfall and the lengths of consecutive dry-day and consecutive wet-day periods[66] indicate that Hawaiʻi's rainfall is becoming more extreme and suggest that both droughts and floods are becoming more frequent in Hawaiʻi. With the addition of more years of observed data, and a more detailed spatiotemporal analysis from a grid-box level down to the island level, this contrasts with the earlier findings of a decreasing trend in the number of extreme rainfall events in Hawaiʻi.[227]

Saltwater contamination due to sea level rise: Sea level rise exacerbates the existing vulnerability of groundwater lenses on small coral islands to contamination by saltwater intrusion by amplifying the impacts of freshwater lens-shrinking droughts and storm-related overwash events.[69]

Major uncertainties

Effects of warming on evapotranspiration: There are uncertainties in how warming will affect cloud cover, solar radiation, humidity, and wind speed. All of these affect potential evapotranspiration and changes in soil moisture, and the effects will differ by region.[228]

Future precipitation changes: Global models differ in their projections of precipitation changes for the Hawaiʻi–USAPI region.[63] For Hawaiʻi, downscaled projections differ according to the choice of global model time horizon, emissions scenario, and downscaling method.[229]

Description of confidence and likelihood

There is *very high confidence* in further increases in temperature in the region, based on the consistent results of global climate models showing continued significant increases in temperature in the Hawaiʻi–USAPI region for all plausible emissions scenarios.

There is *low confidence* regarding projected changes in precipitation patterns, stemming from the divergent results of global models and downscaling approaches and from uncertainties around future emissions. However, for leeward areas of Hawaiʻi and the eastern part of the Federated States of Micronesia (FSM), future decreases in precipitation are somewhat more likely, based on greater agreement between downscaling approaches for Hawaiʻi and greater agreement among global models for eastern FSM.

There is *very high confidence* in future increases in sea level, based on widely accepted evidence that warming will increase global sea level, with amplified effects in the low latitudes.

There is *medium confidence* in the increasing risk of both drought and flood extremes patterns, based on both observed changes (for example, increasing lengths of wet and dry periods) and projected effects of warming on extreme weather globally.

There is *medium confidence* in possible future catastrophic impacts on food and water security resulting from saltwater contamination in low atolls due to sea level rise; this is based on *very high confidence* in continuing sea level rise, the known effects of saltwater contamination on water supply and agriculture, and uncertainty regarding the effectiveness of adaptation measures.

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

> Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism (*very high confidence*). Terrestrial habitats and the goods and services they provide are threatened by rising temperatures (*very likely*, *very high confidence*), changes in rainfall (*likely*, *medium confidence*), increased storminess (*likely*, *medium confidence*), and land-use change (*very likely*, *very high confidence*). These changes promote the spread of invasive species (*likely*, *low confidence*) and reduce the ability of habitats to support protected species and sustain human communities (*likely*, *medium confidence*). Some species are expected to become extinct (*likely*, *medium confidence*) and others to decline to the point of requiring protection and costly management (*likely*, *high confidence*).

Description of evidence base

Projections of sea level rise have been made at both regional and local scales (see Traceable Account for Key Message 3). Based on these projections, the effects of sea level rise on coastal ecosystems have been evaluated for the Northwest Hawaiian Islands.[18,83,84,86,171,228] There has also been an assessment of the effects of climate change to many small islands across the Pacific Islands region.[70] The effect of sea level rise (and global warming) on mangroves has also been evaluated.[86,230,231,232]

Forecasts of how climate change will affect rainfall and temperature in the main Hawaiian Islands have been based on both statistical and dynamical downscaling of global climate models (GCMs; see Traceable Account for Key Message 1). Statewide vulnerability models have been developed for nearly all species of native plants[233] and forest birds,[43] showing substantial changes in the available habitat for many species. More detailed modeling within Hawaiʻi Volcanoes National Park has suggested that rare and listed plants being managed in Special Ecological Areas will experience climate changes that make the habitat in these areas unsuitable.[91]

Effects of climate change on streamflow in Hawaiʻi will largely be driven by changes in rainfall, although geologic conditions affect the discharge of groundwater that provides base flow during dry weather.[234] A regional watershed model from the windward side of Hawaiʻi Island suggested that control of an invasive tree with high water demand would somewhat mitigate decreases in streamflow that might be caused by a drier climate.[44] Finally, it has been suggested that ocean acidification will decrease the viability of the planktonic larvae of native Hawaiian stream fishes.[99]

Major uncertainties

The timing and magnitude of sea level rise are somewhat uncertain. There is greater uncertainty on how climate change will affect the complex patterns of precipitation over the high islands of Hawaiʻi. There is also high uncertainty about how plants will respond to changes in their habitats and the extent to which climate change will foster the spread of invasive species.

Description of confidence and likelihood

It is *very likely* that air and water temperatures will increase and that sea level will rise (*very high confidence*). Research indicates that global mean sea level rise will exceed previous estimates and that, in the USAPI, sea level rise is likely to be higher than the global mean (*likely, high confidence*). As a result, it is *likely* that climate change will affect low-lying and coastal ecosystems in Hawai‘i and other Pacific islands, with *medium confidence* in forecasts of the effects on these ecosystems.

There is *low confidence* as to how rainfall patterns will shift across the main Hawaiian Islands. It is considered *likely* that changes in rainfall will result in ecologic shifts expected to threaten some species. However, there is *low confidence* in specific ecologic forecasts, because the direction and magnitude of rainfall changes are uncertain and there is a lack of robust understanding of how species will respond to those changes. It seems *as likely as not* that the responses of terrestrial biomes and species to climate change will result in additional complexity in the management of rare and threatened species.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economics, housing and energy, transportation, and other forms of infrastructure (*very likely*, *very high confidence*). By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands (*very likely*, *high confidence*). This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience (*likely*, *high confidence*). As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

Description of evidence base

Multiple lines of research have shown that changes in melting in Greenland,[110] the Antarctic,[107] and among alpine glaciers,[111] as well as the warming of the ocean,[113] have occurred faster than expected. The rate of sea level rise is accelerating,[103] and the early signs of impact are widely documented.[9] Relative to the year 2000, global mean sea level (GMSL) is *very likely* to rise 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1.0–4.3 feet (30–130 cm) by 2100 (*very high confidence* in lower bounds; *medium confidence* in upper bounds for 2030 and 2050; *low confidence* in upper bounds for 2100).[17,105] Future greenhouse gas (GHG) emissions have little effect on projected average sea level rise in the first half of the century, but they significantly affect projections for the second half of the century. Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of pathway, it is extremely likely that GMSL rise will continue beyond 2100 (*high confidence*).[105]

Changes in precipitation,[235] Pacific sea level,[4] climate variability,[3] and the unsustainable practices of many human communities among Pacific islands[127] all converge to increase the vulnerability of coastal populations[135] as climate change continues in the future.[55] As sea level rises and average atmospheric temperature continues to increase, wave events[37] associated with changing weather patterns[140] constitute a growing mechanism for delivering[12] damaging saltwater into island aquifer systems,[13] ecosystems,[129] and human infrastructure systems.[17]

In Hawaiʻi, studies by the Hawaiʻi Climate Change Mitigation and Adaptation Commission[42] reveal that with 3.2 feet of sea level rise, over 25,800 acres of land in the state would be rendered unusable. Some of that land would erode into the ocean, some would become submerged by inches or feet of standing water, and some areas would be dry most of the year but repeatedly washed over by seasonal high waves. Statewide, about 34% of that potentially lost land is designated for urban use, 25% is designated for agricultural use, and 40% is designated for conservation. The loss of urban land is expected to increase pressure on the development of inland areas, including those designated as agricultural and conservation lands. Across the state, over 6,500 structures located near the shoreline would be compromised or lost with 3.2 feet of sea level rise. Some of these vulnerable structures include houses and apartment buildings, and their loss would result in over 20,000 displaced residents in need of new homes. The value of projected flooded structures, combined with the land value of the 25,800 acres projected to be flooded, amounts to over $19 billion across the state (in 2013 dollars; $19.6 billion in 2015 dollars). However, this figure does not encompass the full loss potential in the state, as monetary losses that would occur from the chronic flooding of roads, utilities, and other public infrastructure were not analyzed in this report and are expected to amount to as much as an order of magnitude greater than the potential economic losses from land and structures. For example, over 38 miles of major roads would be chronically flooded across the state with 3.2 feet of sea level rise. Utilities, such as water, wastewater, and electrical systems, often run parallel and underneath roadways, making lost road mileage a good indication of the extent of lost utilities. This chronic flooding of infrastructure would have significant impacts on local communities as well as reverberating effects around each island.

The loss of valuable natural and cultural resources across all islands would cost the state dearly, due to their intrinsic value. Beaches that provide for recreation, wildlife habitat, and cultural tradition would erode, from iconic sites such as Sunset Beach on Oʻahu to neighborhood beach access points rarely visited by anyone except local residents. Some beaches would be lost entirely if their landward migration is blocked by roads, structures, shoreline armoring, or geology. The flooding of the more than 2,000 on-site sewage disposal systems with 3.2 feet of sea level rise would result in diminished water quality in streams and at beaches and shoreline recreation areas. The loss of and harm to native species and entire ecosystems would have implications for Hawaiian cultural traditions and practices, which are closely tied to the natural environment. Further, nearly 550 cultural sites in the state would be flooded, and many Hawaiian Home Lands communities would be impacted by flooding. In some cases, inland migration or careful relocation of these natural and cultural resources is expected to be possible. In other cases, the resources are inextricably bound to place and would be permanently altered by flooding.[42]

Marra and Kruk (2017)[142] describe climate trends for the USAPI. Globally and locally, observations of GHG concentrations, surface air temperatures, sea level, sea surface temperature, and ocean acidification show rising trends at an increasing rate. Trends in measures of rainfall, surface winds, and tropical cyclones are not as readily apparent. Patterns of climate variability characterize these measures and tend to mask long-term trends. A lack of high-quality, long-term observational records, particularly with respect to in situ stations, contributes to difficulties in discerning trends. To maintain and enhance our ability to assess environmental change, attention needs to be given to robust and sustained monitoring.

There are consistent subregional changes in the number of days with high winds. The global frequency of tropical cyclones (TCs) appears to be showing a slow downward trend since the early 1970s. In the Pacific region, long-term TC trends in frequency and intensity are relatively flat, with the record punctuated by as many active as inactive years.[142]

Major uncertainties

Major uncertainties lie in understanding and projecting the future melting behavior of the Antarctic and Greenland ice sheets. To date, new observations attest to melting occurring at higher than expected rates. If this continues to be the case, it is plausible for future sea level rise to exceed even worst-case scenarios. Secondary feedbacks to warming, such as changes in the global thermohaline circulation; shifts in major weather elements, such as the intertropical convergence zone and the polar jet stream; and unexpected modes of heat distribution across the hemispheres risk complex responses in the climate system that are not well understood. Pacific climate variability is a governing element that amplifies many aspects of climate change, such as drought, sea level, storminess, and ocean warming. A number of mechanisms through which climate change might alter Pacific variability have been proposed on the basis of physical modeling, but our understanding of the variability remains low, and confidence in projected changes is also low. For instance, in any given Pacific region, our understanding of future TC occurrence, intensity, and frequency is low. Future physical responses to climate change that have not yet been described are possible. These uncertainties greatly limit our ability to identify the chronology of changes to expect in the future.

Description of confidence and likelihood

There is *very high confidence* that a continued rise in global temperature will lead to increases in the rate of sea level rise. There is less confidence in the projected amounts of sea level rise during this century, and there is *low confidence* in the upper bounds of sea level rise by the end of the century. Sea level rise will *very likely* lead to saltwater intrusion, coastal erosion, and wave flooding. It is *very likely* this will strain the sustainability of human infrastructure systems, limit freshwater resources, and challenge food availability. If the high-end projections of future sea level rise materialize, it is *very likely* this will threaten the very existence of Pacific island coastal communities.

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification (*very likely*, *high confidence*). Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue (*likely*, *medium confidence*). Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields, and loss of coastal protection and habitat (*very likely*, *very high confidence*). Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5; *likely*, *medium confidence*).

Description of evidence base

The Key Message was developed based on input from an expert working group convened at the outset of this section development and supported by extensive literature.

Ocean warming: NCA3 documented historical increases in sea surface temperature (SST), and current levels in much of the region have now exceeded the upper range of background natural variation.[32,154] Future increases are projected even under lower-than-current emissions rates.[123,154]

Ocean acidification: Atmospheric carbon dioxide levels recorded at Mauna Loa, Hawai‘i, have recently exceeded 400 parts per million, and oceanic pH levels measured off O‘ahu have steadily declined from an annual average of about 8.11 to 8.07 over the past 25 years (data from Hawai‘i Ocean Time Series, SOEST, University of Hawai‘i) and are projected to decrease to 7.8 by 2100.[123] As pH declines, it lowers the saturation level of aragonite (the form of calcium carbonate used by corals and many other marine organisms), reducing coral and shell growth.[125] By the end of the century, aragonite saturation is projected to decline from a current level of 3.9 to 2.4, representing extremely marginal conditions for coral reef growth.[32,123,159,161]

Bleaching events: These continue to occur—most recently over successive years—with widespread impacts.[45,158] Sea surface temperature time series from a suite of Climate Model Intercomparison Project 5 outputs that are statistically downscaled to 4 km resolution are used to project the year when coral reefs will begin to experience annual bleaching under the higher scenario (RCP8.5).[46] These data forecast that bleaching will be an annual event for the region starting in about 2035.[46]

Mortality: During the 2014–2015 bleaching events, coral mortality in western Hawai‘i was estimated at 50%[45] and over 90% at the pristine equatorial Jarvis Atoll.[156]

Coral reef ecosystem impacts: Coral reef cover around the Pacific Islands region is projected to decline from the current average level of about 40% to 15%–30% by 2035 and 10%–20% by 2050.[123] The loss of coral reef habitat is projected to reduce fish abundance and fisheries yields by 20%.[123] Loss of coral reefs will result in increased coastal erosion.[23,236] Tourism is the major economic engine in Hawai‘i, and healthy coral reef ecosystems are critical to this economy. Under the higher scenario (RCP8.5), coral reef loss is projected to result in a total economic loss of $1.3 billion per year in 2050 and $1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, a lower scenario (RCP4.5) would avoid 16% of coral cover loss and $470 million per year (in 2015 dollars, undiscounted) compared to the higher scenario.[162] The confidence intervals around these loss estimates under RCP8.5 for 2050 range from a gain of $240 million to a loss of $1.9 billion, and for 2090 range from a loss of $1.7 billion to $1.9 billion (in 2015 dollars, undiscounted).[162]

Insular fisheries: Insular fishes, including both coral reef fishes and more mobile, coastal pelagics (species such as mahi mahi and wahoo), are impacted both from declines in carrying capacity and loss from migration in response to temperature change. Taken together, declines in maximum catch potential exceeding 50% from late 20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones of most islands in the central and western Pacific.[163]

Oceanic fisheries: A number of studies have projected that ocean warming will result in lower primary productivity due to increased vertical stratification and loss of biodiversity as organisms move poleward.[129,167,169] Estimates of up to a 50% decline in fisheries yields are projected with two different modeling approaches.[129,169] The impact of climate change specifically on fisheries targeting bigeye, yellowfin, and skipjack tunas in the western and central equatorial Pacific has been explored with fisheries models.[123,237,238] However, there is considerable uncertainty in the projections of population trends, given our lack of understanding of how the various life stages of these species will respond and the sensitivity of the projections to the specific model used.[238,239]

Major uncertainties

A major uncertainty for coral reefs is whether they can evolve rapidly enough to keep up with the changing temperature and pH.[164,165] In the oceanic ecosystem, the impacts of changing ocean chemistry on the entire food web are not well understood but are expected to result in shifts in the composition of the species or functional groups, altering the energy flow to top trophic levels.[240,241] For example, a shift in the micronekton community composition (squids, jellyfishes, fishes, and crustaceans) was projected to alter the abundance of food available to fishes at the top of the food web.[240] The impact of climate change on the intensity and frequency of interannual and decadal modes of climate variability (such as El Niño–Southern Oscillation and Pacific Decadal Oscillation) is not well known but has very important consequences.[1]

Description of confidence and likelihood

There is *high confidence* that fisheries and the livelihoods they support are threatened by warmer ocean temperatures and ocean acidification. Widespread and multiyear coral reef bleaching and mortality are already occurring. It is *likely*, based on modeled SST projections, that by mid-century, bleaching will occur annually with associated mortality.

There is *medium confidence* in the projection of annual bleaching by mid-century, as it does not take into account any adaptation in corals.

There is *high confidence* that bleaching and rising seawater acidity will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection. This is deemed *very likely* because significant coral mortality has recently been observed in western Hawaiian coral reefs that suffered from the 2015 bleaching event. Further, the positive relationship between fish density and coral reef cover is well established. The magnitude of this impact depends on the extent that coral species exhibit adaptive or resilience capacity.

There is *medium confidence* that declines in oceanic fishery productivity of up to 15% and 50% are likely by mid-century and 2100, respectively. These declines are considered *likely* because we have seen related linkages between climate variability such as ENSO and the Pacific Decadal Oscillation and fisheries yields that provide an analog in some ways to global warming impacts. The uncertainty lies in our limited understanding of the linkages and feedbacks in the very complex oceanic food web. As temperate habitats warm, they will likely gain some tropical species, while the tropical habitats will likely only lose species.

Key Message 5

Indigenous Communities and Knowledge

Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing future freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources (*likely*, *high confidence*). Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Description of evidence base

The research supporting this Key Message examines the impacts of climate change on the lands, territories, and resources of the Pacific region and its Indigenous communities.

It is foundational to highlight the interconnectedness and important familial relationship Indigenous peoples have with their lands, territories, and resources. Native Hawaiian attorneys and professors Sproat and Akutagawa discuss the health impacts and threats that climate change poses for Indigenous communities and their relationship with ancestral resources. Sproat states that "any such loss will result in the loss of culture."[177] Further support is found in a community health assessment done by Akutagawa and others that states, "In traditional Hawaiian conceptions of health, personal harmony and well-being are deemed to stem from one's relationship with the land, sea, and spiritual world."[176]

Governments and their support institutions are also sharing outcomes of projects they've initiated over the years that document not only the successes but also the challenges, observations, and lessons learned.[149,179] This includes the recognition of the dominant role of Indigenous women in island communities as gatherers and in household activities; economic development activities like transporting and selling produce;[146] distribution of crops;[179] maintenance of crop diversity, food security, security of income, seed saving, and propagation; transmission of traditional knowledge and practices, especially spiritual practices;[185] and stewarding underwater reef patches and stone enclosures as gardens.[242]

In writing this Key Message, the authors considered the body of research focusing on the impacts of climate change on Pacific communities such as sea level rise,[104,115,147,177,243] ocean acidification,[84,115,147,177,184] and drought.[147,177,179,184,242,243,244] Clear examples used in the studies illustrate the confidence that Indigenous communities are at high risk for experiencing effects at a physical,[176,245] social,[22,175,176,177,184,244] and spiritual level.[21,84,174,175,176,177,245]

There is very strong evidence that traditional knowledge is key to the resilience and adaptive capacity of Indigenous peoples of the Pacific.[21,84,176,180,184,185,242]

Major uncertainties

There is no doubt that Indigenous communities of the Pacific are being impacted by climate change. However, the rate and degree of the impacts on the spiritual, relational, and ancestral connectedness vary from community to community and on the type of practice being impacted. This variable is difficult to document and express in certain circumstances. Additionally, the degree of the impact varies according to the livelihoods of the community and the specific climatic and socioeconomic and political circumstances of the island in question.

Description of confidence and likelihood

There is *high confidence* that climate change is having far-reaching effects on the land security, livelihood security, habitat security, and cultural food security of Indigenous peoples of the Pacific.

It is *likely* that most of these impacts will have negative effects on the cultural heritage of the Pacific island communities.

There is *high confidence* that traditional knowledge together with science will support the adaptive capacity of Pacific island communities to survive on their islands.

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs (*likely*, *medium confidence*). In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods (*likely*, *high confidence*) that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation (*likely*, *high confidence*).

Description of evidence base

For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates and intensity. The frequency of the most intense of these storms is projected to increase in the western North Pacific and in the eastern North Pacific (see also Key Message 3).[246] Studies indicate that Hawaiʻi will see an increased frequency of tropical cyclones (TCs) due to storm tracks shifting northward in the central North Pacific.[40,247]

The *Climate Science Special Report* (CSSR) summarizes extensive evidence that is documented in the climate science literature and is similar to statements made in NCA3 and international[106] assessments.[33] More recent downscaling studies have further supported these assessments,[248] though pointing out that the changes (future increased intensity and TC precipitation rates) will not necessarily occur in all basins.[246]

Damage from TCs is significant. Tropical Cyclone Evan struck Sāmoa in December 2012 and caused damage and losses of approximately $210 million dollars (dollar year not reported), representing 30% of its annual gross domestic product (GDP). Tropical Cyclone Pam struck Vanuatu, Tuvalu, and Kiribati in 2015; in Vanuatu, it killed 11 people and caused approximately $450 million (dollar year not reported) in damages and losses, equal to 64% of GDP.[196]

In the CSSR, future relative sea level rise as shown for the 3.3-feet (1 m) Interagency scenario in 2100 indicates that, because they are far from all glaciers and ice sheets, relative sea level rise in Hawai‘i and other Pacific islands due to any source of melting land ice is amplified by the static-equilibrium effects. Static-equilibrium effects on sea level are produced by the gravitational, elastic, and rotational effects of mass redistribution resulting from ice loss.[105]

Sea level rise across Hawai‘i is projected to rise another 1–3 feet by the end of this century. Sea level rise has caused an increase in high tide floods associated with nuisance-level impacts. High tide floods are events in which water levels exceed the local threshold (set by the National Oceanic and Atmospheric Administration’s National Weather Service) for minor impacts. These events can damage infrastructure, cause road closures, and overwhelm storm drains. Along the Hawaiian coastline, the number of tidal flood days (all days exceeding the nuisance-level threshold) has also increased, with the greatest number occurring in 2002–2003. Continued sea level rise will present major challenges to Hawai‘i’s coastline through coastal inundation and erosion. Seventy percent of Hawai‘i’s beaches have already been eroded over the past century, with more than 13 miles of beach completely lost. Sea level rise will also affect Hawai‘i’s coastal storm water and wastewater management systems and is expected to cause extensive economic impacts through ecosystem damage and losses in property, tourism, and agriculture.[247]

In the Pacific Islands region, population, urban centers, and critical infrastructure are concentrated along the coasts. This results in significant damages during inundation events. In December 2008, wind waves generated by extratropical cyclones, exacerbated by sea level rise, caused a series of inundation events in five Pacific island nations.[9] An area of approximately 3,000 km in diameter was affected, impacting approximately 100,000 people. Across the islands, major infrastructure damage and crop destruction resulted, costing millions of dollars and impacting livelihoods, food security, and freshwater resources.

The increases in the frequency and intensity of climate change hazards, including cyclones, wind, rainfall, and flooding, pose an immediate danger to the Pacific Islands region. A decrease in the return times of extreme events, which will reduce the ability of systems to recover, will likely cause long-term declines in welfare.[181] For small islands states, the damage costs of sea level rise are large in relation to the size of their economies.[194,195]

The social science research on climate and conflict suggests a possible association between climate variability and change and conflict. Consensus or conclusive evidence of a causal link remains elusive. Hsiang et al. (2013)[249] find strong causal evidence linking climatic events to human conflict across a range of spatial scales and time periods and across all major regions of the world. They further demonstrate that the magnitude of climate influence is substantial.[249] Specifically, large deviations from average precipitation and mild temperatures systematically increase the risk of many types of conflict (intergroup to interpersonal), often substantially. Hsiang and Burke (2014)[250] describe their detailed meta-analysis, examining 50 rigorous quantitative studies, and find consistent support for a causal association between climatological changes and various conflict outcomes.[250] They note, however, that multiple mechanisms can explain this association and that the literature is currently unable to decisively exclude any proposed pathway between climatic change and human conflict.[249]

Evidence of the impact of climate on livelihoods is also well established. Barnett and Adger (2003, 2007)[191,197] are among a range of studies that conclude that climate change poses risks to livelihoods, communities, and cultures.[197] These risks can influence human migration. The United Nations Environment Programme finds that the degree to which climatic stressors affect decisions to migrate depend on a household's vulnerability and sensitivity to climatic factors.[206]

Major uncertainties

A key uncertainty remains the lack of a supporting, detectable anthropogenic signal in the historical data to add further confidence to some regional projections. As such, confidence in the projections is based on agreement among different modeling studies. Additional uncertainty stems from uncertainty in both the projected pattern and magnitude of future sea surface temperatures.[33,40,248]

One study projects an increase in tropical cyclone frequency (TCF) of occurrence around the Hawaiian Islands but stipulates that TCF around the Hawaiian Islands is still very low in a warmed climate, so that a quantitative evaluation of the future change involves significant uncertainties.[40]

Uncertainties in reconstructed global mean sea level (GMSL) change relate to the sparsity of tide gauge records, particularly before the middle of the twentieth century, and to the use of a variety of statistical approaches to estimate GMSL change from these sparse records. Uncertainties in reconstructed GMSL change before the 20th century also relate to the lack of geological proxies (preserved physical characteristics of the past environment that can stand in for direct measurement) for sea level change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in attribution relates to the reconstruction of past changes and the magnitude of natural variability in the climate.

Since NCA3, multiple approaches have been used to generate probabilistic projections of GMSL rise. These approaches are in general agreement. However, emerging results indicate that marine portions of the Antarctic ice sheet are more unstable than previously thought. The rate of ice sheet mass changes remains challenging to project.

In sea level rise projections, Antarctic contributions are amplified along U.S. coastlines, while Greenland contributions are dampened; regional sea level is projected to be higher than if driven by a more extreme Greenland contribution and a somewhat less extreme Antarctic contribution.[17]

The degree to which climate variability and change impact conflict, and related causal pathways, remains uncertain. This is compounded by the fact that different types of conflict—social, political, civil, or violent—are conflated.[209,251] Violent conflict can describe interpersonal-, intergroup-, and international-level disputes. Some researchers contend that systematic research on climate change and armed conflict has not revealed a direct connection.[252] Gemenne et al. (2014)[208] argue that there is a lack of convincing empirical evidence or theories that explain the causal connection between climate change and security. They do, however, note that there is some evidence for statistical correlation between climatic changes and conflict, broadly referenced.

Gemenne et al. (2014)[208] also note that the relationship between climate change and security comes from observation of past patterns and that present and projected climate change have no historical precedent. In effect, understanding past crises and adaptation strategies will no longer be able to help us understand future crises in a time of significant climate change.

The degree to which climate variability and change affect migration decisions made today also remains uncertain. This is in part due to the diverse scenarios that comprise climate migration, which themselves result from multiple drivers of migration.[251] Burrows and Kinney (2016)[251] detail examples of climate extremes leading to migration conflicts since 2000, yet they note that there are surprisingly few case studies on recent climate extremes that lead to migration and conflict specifically, despite an increasing body of literature on the theory.

While researchers disagree as to the degree to which climate change drives conflict and migration and the causal pathways that connect them, there is agreement that further research is needed. Buhaug (2015)[252] and Gemenne et al. (2014)[208] argue for research to develop a more refined theoretical understanding of possible indirect and conditional causal connections between climate change and, specifically, violent conflict.[252] Hsiang and Burke (2014)[250] would like additional research that reduces the number of competing hypotheses that attempt to explain the overwhelming evidence that climatic variables are one of many important causal factors in human conflict.[250] Burrows and Kinney (2016)[251] explore the potential pathways linking climate change, migration, and increased risk of conflict and argue that future research should focus on other pathways by which climate variability and change are related to conflict, in addition to the climate–migration–conflict pathway. Kallis and Zografos (2014)[209] seek greater understanding of the potential harm of certain climate change adaptation measures that have the potential to result in maladaptation by spurring conflict.

Description of confidence and likelihood

There is *medium confidence* that climate change will yield compounding economic, environmental, social, and cultural costs. There is greater evidence of these compounding costs resulting from extreme events that are exacerbated by climate change.

There is *high confidence* that food and water insecurity will result in severe disruptions to livelihoods, including the displacement and relocation of island communities.

It is *likely* that the absence of interventions will result in the costly and lengthy rebuilding of communities and livelihoods and more displacement and relocation. Events have played out repeatedly across the region and have resulted in damage, disruptions, and displacements.

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28 Reducing Risks Through Adaptation Actions

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28

Reducing Risks Through Adaptation Actions

Seawall surrounding Kivalina, Alaska

Key Message 1

Adaptation Implementation Is Increasing

Adaptation planning and implementation activities are occurring across the United States in the public, private, and nonprofit sectors. Since the Third National Climate Assessment, implementation has increased but is not yet commonplace.

Key Message 2

Climate Change Outpaces Adaptation Planning

Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past. Incorporating information on current and future climate conditions into design guidelines, standards, policies, and practices would reduce risk and adverse impacts.

Key Message 3

Adaptation Entails Iterative Risk Management

Adaptation entails a continuing risk management process; it does not have an end point. With this approach, individuals and organizations of all types assess risks and vulnerabilities from climate and other drivers of change (such as economic, environmental, and societal), take actions to reduce those risks, and learn over time.

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term. Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security.

Key Message 5

New Approaches Can Further Reduce Risk

Integrating climate considerations into existing organizational and sectoral policies and practices provides adaptation benefits. Further reduction of the risks from climate change can be achieved by new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems.

Executive Summary

Across the United States, many regions and sectors are already experiencing the direct effects of climate change. For these communities, climate impacts—from extreme storms made worse by sea level rise, to longer-lasting and more extreme heat waves, to increased numbers of wildfires and floods—are an immediate threat, not a far-off possibility. Because these impacts are expected to increase over time, communities throughout the United States face the challenge not only of reducing greenhouse gas emissions, but also of adapting to current and future climate change to help mitigate climate risks.

Adaptation takes place at many levels—national and regional but mainly local—as governments, businesses, communities, and individuals respond to today's altered climate conditions and prepare for future change based on the specific climate impacts relevant to their geography and vulnerability. Adaptation has five general stages: awareness, assessment, planning, implementation, and monitoring and evaluation. These phases naturally build on one another, though they are often not executed sequentially and the terminology may vary. The Third National Climate Assessment (released in 2014) found the first three phases underway throughout the United States but limited in terms of on-the-ground implementation. Since then, the scale and scope of adaptation implementation have increased, but in general, adaptation implementation is not yet commonplace.

One important aspect of adaptation is the ability to anticipate future climate impacts and plan accordingly. Public- and private-sector decision-makers have traditionally made plans assuming that the current and future climate in their location will resemble that of the recent past. This assumption is no longer reliably true. Increasingly, planners, builders, engineers, architects, contractors, developers, and other individuals are recognizing the need to take current and projected climate conditions into account in their decisions about the location and design of buildings and infrastructure, engineering standards, insurance rates, property values, land-use plans, disaster response preparations, supply chains, and cropland and forest management.

In anticipating and planning for climate change, decision-makers practice a form of risk assessment known as iterative risk management. Iterative risk management emphasizes that the process of anticipating and responding to climate change does not constitute a single set of judgments at any point in time; rather, it is an ongoing cycle of assessment, action, reassessment, learning, and response. In the adaptation context, public- and private-sector actors manage climate risk using three types of actions: reducing exposure, reducing sensitivity, and increasing adaptive capacity.

Climate risk management includes some attributes and tactics that are familiar to most businesses and local governments, since these organizations already commonly manage or design for a variety of weather-related risks, including coastal and inland storms, heat waves, water availability threats, droughts, and floods. However, successful adaptation also requires the often unfamiliar challenge of using information on current and future climate, rather than past climate, which can prove difficult for those lacking experience with climate change datasets and concepts. In addition, many professional practices and guidelines, as well as legal requirements, still call for the use of data based on past climate. Finally, factors such as access to resources, culture, governance, and available information can affect not only the risk faced by different populations but also the best ways to reduce their risks.

Achieving the benefits of adaptation can require up-front investments to achieve longer-term savings, engaging with differing stakeholder interests and values, and planning in the face of uncertainty. But adaptation also presents challenges, including difficulties in obtaining the necessary funds, insufficient information and relevant expertise, and jurisdictional mismatches.

In general, adaptation can generate significant benefits in excess of its costs. Benefit–cost analysis can help guide organizations toward actions that most efficiently reduce risks, in particular those that, if not addressed, could prove extremely costly in the future. Beyond those attributes explicitly measured by benefit–cost analysis, effective adaptation can also enhance social welfare in many ways that can be difficult to quantify and that people will value differently, including improving economic opportunity, health, equity, security, education, social connectivity, and sense of place, as well as safeguarding cultural resources and practices and environmental quality.

A significant portion of climate risk can be addressed by mainstreaming; that is, integrating climate adaptation into existing organizational and sectoral investments, policies, and practices, such as planning, budgeting, policy development, and operations and maintenance. Mainstreaming of climate adaptation into existing decision processes has already begun in many areas, such as financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management. Further reduction of the risks from climate change, in particular those that arise from futures with high levels of greenhouse gas emissions, calls for new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems.

Five Adaptation Stages and Progress

The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. *From Figure 18.1* (*Source: adapted from National Research Council, 2010.*[1] *Used with permission from the National Academies Press, ©2010, National Academy of Sciences*).

Introduction

Many regions and sectors across the United States already experience significant impacts from climate change effects, and many of these effects are projected to increase. By the middle of this century, annual losses in the United States due to climate change could reach hundreds of billions of dollars (Ch. 29: Mitigation).[2]

Adaptation refers to actions taken at the individual, local, regional, and national levels to reduce risks from even today's changed climate conditions and to prepare for impacts from additional changes projected for the future.[3,4,5,6]

Adaptation is a form of risk management. Risk is sometimes defined as the likelihood of an event's occurrence multiplied by a measure of its consequences for human and natural systems. But because the probabilities and consequences of climate change threats are often not known with precision, and because different people often value the same consequences differently, it is useful to define risk more broadly as "the potential for adverse consequences when something of value is at stake, and the outcome is uncertain."[7] Risk arises from the combination of exposure to climate hazards, sensitivity to those hazards, and adaptive capacity. Adaptation can, however, provide significant societal benefits, reducing by more than half the cost of climate impacts in some sectors (Ch. 29: Mitigation).[8]

Adaptation involves managing both short- and long-term risks. Many important climate-influenced effects—storm intensity, sea level, frequency of heat waves—have already changed due to past greenhouse gas (GHG) emissions and will continue to change in the decades ahead.[3,4] Because several GHGs, in particular carbon dioxide, reside in the atmosphere for decades or longer, many climate-influenced effects are projected to continue changing through 2050, even if GHG emissions were to stop immediately. Thus, climate risk management requires adaptation for the next several decades, independent of the extent of GHG emission reductions. After 2050, the magnitude of changes, and thus the demands on adaptation, begins to depend strongly on the scale of GHG emissions reduction today and over the coming decades.[4,9]

Individuals, business entities, governments, and civil society as a whole can take adaptation actions at many different scales. Some of these are changes to business operations, adjustments to natural and cultural resource management strategies, targeted capital investments across diverse sectors, and changes to land use and other policies. Adaptation actions can yield beneficial short-term and/or longer-term outcomes in excess of their costs, based on economic returns, ecological benefits, and broader concepts of social welfare and security. Moreover, many strategies can provide multiple benefits, resulting in long-term cost savings. For example, restoring wetlands can provide valuable habitat for fish and wildlife as well as flood protection to nearby communities,[10] and conserving mangrove ecosystems can protect coastal communities from damaging storms[11] as well as help to store carbon.[12]

People are not uniformly vulnerable to climate change. Access to resources, culture, governance, and information affects the risks faced by different populations and partly determines the best ways to reduce their risks.[13] Achieving the benefits of adaptation can require up-front investments to achieve longer-term savings, engaging with differing stakeholder interests and values, and planning in the face of uncertainty.

Integrating climate risk management into existing design, planning, and operations workflows (or mainstreaming), in contrast to adding novel decision processes for climate adaptation alone, can provide many adaptation benefits.[14,15,16] Additional climate risk reduction, particularly under the most severe longer-term climate change projections, emphasizes the need for more and more significant changes to regulatory and policy environments at all scales, to cultural and community resource planning, to economic and financial systems, to technology applications, and to ecosystems.

Key Message 1

Adaptation Implementation Is Increasing

Adaptation planning and implementation activities are occurring across the United States in the public, private, and nonprofit sectors. Since the Third National Climate Assessment, implementation has increased but is not yet commonplace.

Adaptation has five general stages: 1) awareness, 2) assessment, 3) planning, 4) implementation, and 5) monitoring and evaluation, as shown in Figure 28.1,[17,18] although these are also known by other terms (see, for example, the U.S. Climate Resilience Toolkit at https://toolkit.climate.gov/ and the University of Notre Dame's Collaboratory for Adaptation to Climate Change at http://gain.nd.edu). Adaptation is an ongoing process in which organizations and individuals repeatedly cycle through the process shown in Figure 28.1, though specific adaptation efforts can follow different routes through these stages (e.g., California Emergency Planning Agency and California Natural Resources Agency 2012[19]).

The Third National Climate Assessment (NCA3) found that the first three stages were underway throughout the United States but with limited on-the-ground implementation.[18] Since then, the scale and scope of adaptation implementation have increased, including by federal, state, tribal, and local agencies (see Vogel et al. 2017, Halofsky et al. 2015, Leggett 2015, Ray and Grannis 2015, Wentz 2017, and the many examples of adaptation implementation in this chapter and elsewhere in this report[14,20,21,22,23]). For instance, Miami-Dade County's Capital Improvement Program is addressing hazards related to sea level rise, as is San Francisco's 2015 Seawall Resiliency Project. It remains difficult, however, to tally the extent of adaptation implementation in the United States because there are no common reporting systems, and many actions that reduce climate risk are not labeled as climate adaptation.[14] Enough is known, however, to conclude that adaptation implementation is not uniform nor yet common across the United States.[24]

Adaptation actions in the United States have increased in part due to 1) the growing awareness of climate-related threats and impacts and the risks these pose to business operations and supply chains (Ch. 16: International, KM 1), critical public infrastructure and communities, natural areas and public lands, and ecosystems; 2) the wider recognition that investing in adaptation provides economic and social benefits that exceed the costs; and 3) the increasing number and magnitude of extreme events that have occurred.[14]

Five Adaptation Stages and Progress

Figure 28.1: The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. Source: adapted from National Research Council, 2010.[1] Used with permission from the National Academies Press, ©2010, National Academy of Sciences.

Box 28.1: Department of Housing and Urban Development National Disaster Resilience Competition

Rebuild by Design is a design-driven approach to create innovative local resilience solutions conducted in the aftermath of Superstorm Sandy (http://www.rebuildbydesign.org/about#comp456). It was structured to connect local communities with some of the Nation's leading design firms to identify and solve problems collaboratively and to address vulnerabilities exposed by Superstorm Sandy. The design solutions for the winning proposals ranged in scope and scale from large-scale green infrastructure projects to small-scale residential resilience retrofits. The competition process strengthened the understanding of regional interdependencies, fostering coordination and resilience both at the local level and across the United States. Ultimately, nine projects were selected for implementation and received Community Development Block Grant-Disaster Recovery funding totaling $930 million.

While the level of implementation is now higher than at the time of NCA3, the scale of adaptation implementation for some effects and locations seems incommensurate with the projected scale of climate threats.[25] Communities have focused more on actions that address current variability and recent extreme events than on actions to prepare for future change and emergent threats.[14] Communities are currently focused more on capacity building and on making buildings and other assets less sensitive to climate impacts. Communities have been less focused on reducing exposure through actions such as land-use change (preventing building in high-risk locations) and retreat. Furthermore, many communities' adaptation actions arise and are funded in the context of recovery after an event, rather than taken proactively. Often, such adaptation is not as comprehensive as suggested by best practice guidance, as when adaptation plans address sea level rise but not other climate impacts. Few current adaptation plans seek to exploit synergies among various types of actions, and many plans pay little attention to the costs of actions or their co-benefits. Often explicit attention to evaluation and monitoring is scant or nonexistent.

Managing the Challenge

Public- and private-sector decision-makers have traditionally made plans assuming that the current and future climate will resemble the recent past, an assumption known as stationarity.[27] The assumption is often made explicitly. For instance, in order to design a new dam or to negotiate contracts on future deliveries of hydropower and irrigation water, a water agency might use probability distributions for precipitation and extreme flow events that are based on past or current streamflows in a watershed. In other cases, this assumption is made implicitly, as when a city issues building permits for coastal properties using current flood maps without updating them to reflect projected sea level rise.

Box 28.2: Adaptation Actions by Individuals

Many jurisdictions publish guidance to help individuals take actions to reduce the risks from natural hazards. For example, the city of Chicago suggests residents in flood-prone areas take the following actions **before a flood**:[26]

- Avoid building in a floodplain unless you elevate and reinforce your home.
- Elevate the furnace, water heater, and electric panel if susceptible to flooding.
- Install check valves in sewer traps to prevent floodwater from backing up into your home.
- Construct barriers (levees, beams, sandbags, and floodwalls) to stop floodwater from entering the building.
- Seal walls in basements with waterproofing compounds to avoid seepage.
- Keep an adequate supply of food, candles, and drinking water in case you are trapped inside your home.

Key Message 2

Climate Change Outpaces Adaptation Planning

Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past. Incorporating information on current and future climate conditions into design guidelines, standards, policies, and practices would reduce risk and adverse impacts.

The assumption that current and future climate threats and impacts will resemble those of the past is no longer reliably true.[4,27,28] Human-caused carbon pollution in the atmosphere has already pushed many climate-influenced effects—such as the frequency, intensity, or duration of some types of storms and extreme heat, drought, and sea level rise—outside the range of recorded recent natural variability.[4,6,28,29] In addition, improved understanding of climate and Earth system science since the advent of systematic data collection in the 19th century has made it clear that the natural variability of the climate system at regional scales is much larger in places than previously understood. For instance, the southwestern United States was much wetter in the 20th century than in most of the preceding thousand years.

The deviation of climate patterns from the recent historical record is expected to grow even larger in the future because of continuing GHG emissions and because the full impact of previous emissions has not yet been felt due to long delays in the climate system's response to those emissions.[3,4,28] Failure to anticipate and adjust to these changes could be costly.

Adjusting to projected climate risk, rather than relying on interpretations of past impacts, has important implications for the location and design of built human infrastructure, engineering standards, insurance rates, property values, land-use plans and planning frameworks or processes, disaster response preparations, and cropland and forest management. In many respects, such climate risk management has attributes familiar to many decision-makers in businesses and communities that commonly manage or design now for a variety of weather-related risks, including storms, heat waves, water availability threats, and floods. Most organizations also manage other short- and longer-term risks and thus have direct experience with preparing for uncertain future conditions over multiple timescales.

However, climate adaptation is also less familiar to some individuals and organizations in that it requires a complete reversal from the near-universal current assumption of an unchanging climate. Many factors make the reversal of this assumption difficult, including unfamiliarity with climate change datasets and concepts; the need to differentiate among the timescales of weather and climate; the challenge of balancing slow-moving, chronic threats and faster, acute ones; the potential and unknown cascading effects of large-scale global changes on local and regional impacts;[30] and a lack of public awareness that some current and future changes in climate will be slow to accumulate but will take even longer in time to reverse, for the changes that are reversible.[31]

The timescales of climate threats also generally do not align with the scales of governance, impeding adaptation progress and often hindering problem identification and solving. Climate change introduces an unfamiliar new source of uncertainty. Where previously an organization may have created plans using a single, well-understood historical record to project a single set of future climate conditions, it now often faces large numbers of climate model projections produced with myriad uncertainties whose local implications may differ significantly across each projection.

Key Message 3

Adaptation Entails Iterative Risk Management

Adaptation entails a continuing risk management process; it does not have an end point. With this approach, individuals and organizations of all types assess risks and vulnerabilities from climate and other drivers of change (such as economic, environmental, and societal), take actions to reduce those risks, and learn over time.

To grapple with these challenges, organizations have adopted a wide variety of approaches that, to varying degrees, address the five general stages of adaptation listed above. Iterative risk management provides a comprehensive framework and set of processes appropriate for addressing adaptation challenges.[32,33,34,35,36] The framework includes steps for anticipating, identifying, evaluating, and prioritizing current and future climate risks and vulnerabilities; for choosing an appropriate allocation of effort and resources toward reducing these risks; and for monitoring and adjusting actions over time while continuing to assess evolving risks and vulnerabilities. Risk communication accompanies each of these steps.[33,37,38,39] Iterative risk management helps address equity, economics, and other measures of social well-being and supports participatory stakeholder processes, which can enhance transparency and foster defensible decision-making, an important component of successful adaptation efforts.[40]

Iterative risk management emphasizes that the process of anticipating and responding to climate change does not constitute a single set of judgments at any point in time; rather, it is an ongoing cycle of assessment, action, reassessment, learning, and response.[41] The process helps manage risks that are well known, as well as those that are deeply uncertain due to data limitations or the irreducible unpredictability of some aspects of current and future climate.[33,42]

Iterative risk management is consistent with most of the elements in the many climate adaptation efforts and approaches currently in use,[42,43] including climate vulnerability assessment, iterative risk assessment, and adaptive management as often practiced by federal and other land and resource management agencies,[44] as well as disaster risk management.[45] Using a comprehensive framework helps highlight commonalities and differences across the approaches used by different jurisdictions and sectors, facilitating comparison and learning among their users. It also situates climate adaptation squarely within the broad range of other risk management activities, such as in the financial, engineering, environmental, health, and national security sectors.[2]

Adaptation Actions to Reduce Risk

Steps to implementing iterative risk management help decision-makers compare and allocate investments and identify incentives for managing and reducing risk. The planning and implementation steps of the generalized adaptation framework combine several types of actions[46,47,48,49] that

1. reduce exposure (for example, reduce the presence of people or assets in locations that could be adversely affected by climate impacts);

2. reduce sensitivity (that is, lower the degree to which a system is adversely affected by exposure to climate impacts); and

3. increase adaptive capacity (that is, raise the ability of human and natural systems to prepare for, adjust to, respond to, and recover from experienced or anticipated climate impacts).

For instance, in the time since Superstorm Sandy, New York City has reduced its potential future flood impacts by relocating a limited number of households out of the most flood-prone areas (reduced exposure), raising the height of some structures above the ground so they suffer less damage from any flooding (reduced sensitivity), and training the officials responsible for revising building codes and land-use policies to use the most up-to-date estimates of flood risk (increased adaptive capacity). Enhancing social cohesion—the degree to which those in a community identify with the community and with each other—is also known to increase adaptive capacity, such as the ability to rebound quickly from disasters.[50] More broadly, while adaptive capacity often refers only to the targets of adaptation action (such as communities, ecosystems, and infrastructure), "the ability of institutions themselves to adjust and evolve will be key to their ability to manage for change."[51]

Different populations also have different exposure, sensitivity, and adaptive capacity based on their access to resources and information, their culture, and the quality of governance. Such consideration can usefully inform decisions about the equitable and just allocation of resources in reducing climate risk.[52]

Adapting to Current Variability and Preparing for Future Change

Adaptation addresses two timescales: 1) adapting to current variability, which in any particular location may now be different than suggested by the historical record of climate observations, and 2) preparing for future change. This distinction is useful because some decision-makers may not appreciate the extent to which climate has already changed and because these timescales often call for different types of adaptation actions.

Miami Beach is currently raising the level of its roads and building seawalls to reduce current flooding due to higher sea levels, but it is also choosing the height of these new structures, anticipating that sea levels will be even higher in the future.[53] New York City and the Federal Emergency Management Agency (FEMA) agreed to develop two sets of flood maps, one showing current risk for the purpose of setting insurance rates and the other for the longer-term purposes of setting building codes and land-use planning.[54] The National Park Service, working with the U.S. Army Corps of Engineers, constructed a revetment, or retaining wall, and living shoreline in 2013 to protect the Cockspur Island Lighthouse in Georgia's Fort Pulaski National Monument against erosion and accelerated sea level rise. The new revetment incorporated a wider base than is currently required, enabling the addition of rock to extend its height as sea levels rise in the future.[55] The State of Louisiana's Coastal Protection and Restoration Authority's 2017 Coastal Master Plan has more than 100 structural and coastal restoration projects designed to provide benefits over the next decade and up to 50 years into the future.[56]

These timescale differences relate to the ubiquitous term resilience[57] that is frequently employed in adaptation planning under a spectrum of meanings.[58,59] These range from the ability to withstand and recover from current shocks and stressors while retaining basic functions under conditions of existing and near-term variability to the ability to transform in desirable ways over time as the magnitude of change increases.[60,61,62,63,64,65] Recognizing these timescales in planning, and communicating expectations for change along those timelines, can also help communities maximize benefits in the near term and identify the most important opportunities for longer-term well-being and resilience.

Organizations are increasingly exploring alternative approaches for replacing the assumption of an unchanging (or stationary) climate in their risk management activities. Vulnerability assessments, a common practice among managers of public lands and natural areas, often evaluate exposure, sensitivity, and adaptive capacity, and provide rankings of the seriousness of various climate risks. Multi-objective approaches, such as structured decision-making,[66] explicitly include multiple measures of well-being in risk assessment and management, often in difficult areas such as protecting cultural resources.[40] Scenarios are used to 1) assess risks over a range of plausible futures that include both changes in socioeconomic trends as well as climate and 2) choose adaptation actions robust over this wide range of futures.[18] California's 2018 Sea-Level Rise Guidance includes probabilistic sea level rise projections and a worst-case scenario, then integrates both with an adaptive pathways approach[67] that encourages robust and flexible plans that can adjust over time if seas rise faster than expected.

Climate risk management requires addressing socioeconomic (for example, future economic, technology, and regulatory conditions) as well as climate uncertainties. Risk management can address such uncertainties, even when they are difficult to characterize with confidence (Ch. 17: Complex Systems, KM 3).[42,68,69,70,71] The water sector is pioneering approaches for incorporating such information in water utility adaptation, including scenarios and other robust decision methods aimed at making successful decisions insensitive to a wide range of uncertainty.[72] Some agencies are beginning to combine both multi-objective and multi-scenario approaches in quantitative tools that identify vulnerabilities and evaluate tradeoffs among adaptive pathways, seeking risk management strategies that perform well across multiple scenarios and measures of well-being.[73,74,75,76] Implementing such methods can require a more complete set of system models than some agencies commonly use in their planning routines, though such tools are becoming increasingly available.[77]

Benefits of Adaptation Can Exceed the Costs

Adaptation can generate significant benefits in excess of its costs. Nationally, estimates of adaptation costs range from tens to hundreds of billions of dollars per year[78,79] but are expected to save several times that over the long run (Ch. 29: Mitigation).[80] The benefits and costs are larger in scenarios with high emissions. Formal benefit analysis is still in its early stages,[81,82] and more research is needed to assess comprehensively the benefits of specific strategies being considered by individuals and organizations.[83] Nonetheless, experience is growing. For instance, the U.S. Department of Housing and Urban Development's National Disaster Resilience Competition required applications to conduct benefit–cost analysis including qualitative and difficult-to-quantify co-benefits, such as economic revitalization and other social benefits.[84]

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term. Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security.

To date, there exists considerable guidance on actions in some sectors where benefits exceed costs, though guidance is lacking in many other sectors.[83] Benefit–cost information exists for adaptation responses to storms and rising seas in coastal zones, to riverine and extreme precipitation flooding, and for agriculture at the farm level.[85,86] Some of the actions in these sectors, at least in some locations, appear to have large benefit–cost ratios, both in addressing current variability and in preparing for future change. A benefit–cost ratio greater than 1 suggests a promising project to undertake, because the benefits it generates are greater than its costs. For instance, while sandbags protecting individual houses can, in general, have benefit–cost ratios less than 1, in South Florida sandbags can have a benefit–cost ratio of 20 to 1,[87] and along the Gulf of Mexico coastline, 3 to 1.[88] Along the Gulf of Mexico coastline, levees and seawalls can have benefit–cost ratios ranging from 2.3 to 1.5 to 1 for refineries and petrochemical plants, though the ratios are lower for other assets.[88]

Information on the cost of actions that can achieve common goals is increasing in the water management sector, such as for operational reliability and resilience and environmental protection (Ch. 3: Water) and for responding to extreme heat events (Ch. 14: Human Health). Loss of water services or power during a high heat event, for example, can produce considerable costs that can have cascading effects on other sectors, thereby further driving up costs.[89] The benefits of these adaptive actions against these threats have been studied less because they involve societal and environmental impacts that have been more difficult to quantify, study, and describe systematically.

Some studies quantify large benefits from adaptation actions involving natural systems,[90] such as the decommissioning and restoration of unused forest roads, which decreases erosion and improves fish habitat and water quality; the restoration of beavers to mountain areas, whereby beaver dams improve fish habitat and improve water supply during summer months; and treatment of hazardous fuel to reduce wildland fire risks (Ch. 6: Forests). Some types of storm water management also show large benefits from green infrastructure and other nature-based responses.[91,92] Coastal marsh restoration can sometimes provide benefits of protection against rising sea levels, along with added flood prevention and enhanced biodiversity. One effort involves restoring the river and surrounding lands of the Tidmarsh Wildlife Sanctuary in coastal Massachusetts, a former cranberry farm. The project includes cutting-edge environmental sensors that provide continuous data on marsh restoration, cranberry farm conversion, and climate change impacts and adaptation (see http://www.livingobservatory.org).

Extensive co-benefits may also be available from adaptation, in particular in the ecosystem services and health sectors (Ch. 7: Ecosystems; Ch. 14: Human Health). Coordinated adaptation and GHG mitigation planning may also provide defined co-benefits (Ch. 29: Mitigation, KM 4). For instance, tools are available to help decision-makers locate wind energy systems away from sensitive ecological sites, without incurring additional costs (for example, see the Nature Conservancy's Biodiversity and Wind Siting Mapping Tool at https://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newyork/climate-energy/working-with-wind.xml). Designs that provide green space and the use of cool and green roof technologies in cities can reduce heat-island effects, producing multiple benefits and cost reductions by helping to reduce emissions and air pollution, human health risks, and economic losses due to reduced labor productivity.[93,94]

Broader Measures of Well-Being Benefit–cost analysis provides one important, but not the sole, means to evaluate alternative adaptation actions. Effective adaptation can provide a broad range of benefits that can be difficult to quantify, including improvements in economic opportunity, human health, equity, national security, education, social connectivity, and sense of place, while safeguarding cultural resources and practices and enhancing general environmental quality. Aggregating all these benefits into a single monetary value is not always the best approach,[8,95] since in many cases a lack of data and uncertainty over climate projections and benefit valuations may make it impossible to give a uniform treatment to different types of benefits, thereby implicitly favoring some over others. More fundamentally, different people may value benefits differently.[96] For instance, climate change can have significant impacts on equity and ecosystems, even though individuals can have strongly divergent views on distributional justice and the intrinsic value of nature and thus on how they value such impacts.

Considering various types of outcomes separately in risk management processes—termed multi-objective or multi-criteria analysis in the relevant literature[97]—can facilitate participatory planning processes. This also enhances the fairness of such processes by making more explicit the impacts of climate change on outcomes to different stakeholders, along with the policy tradeoffs among those outcomes. Pittsburgh's EcoInnovation District, in the city's Uptown and Oakland neighborhoods, employs bottom-up planning to improve the environment, support the needs of existing residents, and expand job growth. Louisiana's Comprehensive Master Plan for a Sustainable Coast has five broad objectives: reduce economic losses from flooding, promote sustainable coastal ecosystems, provide coastal habitats that support commerce and recreation, sustain the region's unique cultural heritage, and contribute to the regional and national economy by promoting a viable working coast.[56] The plan contains actions that advance all five objectives, reflecting a set of tradeoffs broadly acceptable to diverse communities in the face of hazards, including coastal subsidence (sinking land) and sea level rise.[98]

Risk management approaches that consider multiple objectives can include a specific focus on equity, with important implications on the content and process of adaptation planning and action.[99] Poor or marginalized populations often face a higher risk from climate change because they live in areas with higher exposure, are more sensitive to climate impacts, or lack adaptive capacity (Ch. 14: Human Health; Ch. 15: Tribes). Prioritizing adaptation actions for such populations may prove more equitable and lead, for instance, to improved infrastructure in their communities and increased focus on efforts to promote social cohesion and community resilience that can improve their capacity to prepare, respond, and recover from disasters. Equity considerations can also lead to the expanded participation of poor or marginalized populations in adaptation planning efforts. This can enhance the fairness of the process. Moreover, it can positively affect choices regarding the appropriate balance among the resources invested in reducing climate risk and those put toward other social goals, such as employment and education, and inform the most appropriate mix of adaptation actions in each community.[52] Also, at the state and national level, equity considerations for climate adaptation can help allocate an appropriate distribution of resources for adaptation among different local communities.

Key Message 5

New Approaches Can Further Reduce Risk

Integrating climate considerations into existing organizational and sectoral policies and practices provides adaptation benefits. Further reduction of the risks from climate change can be achieved by new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems.

A significant portion of climate risk can be addressed by mainstreaming; that is, integrating climate adaptation into existing organizational and sectoral investments, policies, and practices. Mainstreaming can make adaptation more likely to succeed because it augments already familiar processes with new information and tools, rather than requiring extensive new structures.[100,101,102] Mainstreaming can also encourage risk management actions that synergistically and coherently address adaptation along with other societal objectives. Mainstreaming can also prompt innovation in existing organizational structures[103,104] by improving their treatment of all types of uncertainty. However, mainstreaming can diminish the visibility of climate adaptation relative to dedicated, stand-alone adaptation approaches[105] and may prove insufficient to address the full range of climate risk, in particular the risks associated with higher GHG concentrations.

Integrating climate adaptation into existing risk management processes requires including climate risks with the other risks an organization regularly assesses and manages; explicitly linking actions that address current climate variability with those needed to address larger, future changes; and linking policies across sectors (for example, energy and water) and jurisdictions. Much adaptation action occurs at the local level, so such linking can be horizontal (that is, among agencies within the same local jurisdiction) and vertical (that is, among different levels of local, state, tribal, and federal governments).[104]

Existing Mainstreaming

Mainstreaming climate adaptation into existing decision processes has begun in many areas, in particular those with well-developed risk management processes such as financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management.

A growing number of jurisdictions address climate risk in their land-use, hazard mitigation, capital improvement, and transportation plans. In 2015, FEMA began requiring states to include the projected effects of climate change in their state hazard mitigation plans.[106] A small number of cities explicitly link their coastal plans and their hazard mitigation plans using a common, climate-informed vulnerability analysis to support both types of plans, thereby ensuring that the different city agencies are implementing risk reduction measures—such as land-use measures (reducing exposure), building codes (reducing sensitivity), and warning, evacuation, and recovery measures (increasing adaptive capacity)—that are synergistic and coordinated.[107] The City of Baltimore used climate-informed estimates of increased current and future storm intensity to design its storm water master plan, which includes green space and bio-swales that capture runoff, to improve water quality and reduce flood risk. California requires its water agencies to address climate change in their water management plans. Through the Department of Energy (DOE) Partnership for Energy Sector Climate Resilience, electric utilities across the country are collaborating with DOE to develop resilience planning guidance, conduct climate change vulnerability assessments, and develop and implement cost-effective resilience solutions (Ch. 4: Energy). The National Oceanic and Atmospheric Administration (NOAA), FEMA, and the U.S. Geological Survey are partnering with states to develop guidelines for integrated climate adaptation, land use, and hazard mitigation planning. Federal agencies have also begun implementing climate-smart management approaches for managing their natural resources (Ch. 7: Ecosystems, KM 2).

Private financial markets are increasingly paying attention to climate risk, for instance, by incorporating such risk accounting into their portfolios. In some cases, financial firms and companies perform climate risk accounting as part of a voluntary or mandatory disclosure system. In a recent report to the G20 (Group of Twenty), the Financial Stability Board's Task Force on Climate-Related Financial Disclosures provided a comprehensive framework for such disclosure and recommended that since "climate-related risks are material risks," they should be disclosed in mainstream (public) financial filings.[108,109] Ratings agencies have also begun to incorporate physical climate risk into credit ratings for corporations, infrastructure bonds, and other public-sector projects. Both Moody's and Standard and Poor's acknowledge emerging risks associated with climate change[110,111] and now embed these risks into their credit ratings.[112] In particularly vulnerable areas, such as South Florida, bond ratings are now beginning to reflect such risks.

The engineering community has begun incorporating climate resilience into its design standards by incorporating information about current and future climate threats and impacts[113] and updating existing engineering standards, codes, regulations, and practic- es—currently based on stationary climate assumptions.[114] The American Society of Civil Engineers (ASCE) recommends that engineers incorporate climate uncertainty, assess the costs of reducing risks, and follow an adaptive management process. Such a process would begin with low-regret strategies that perform well across a range of futures and periodically update as new information becomes available.[113] The ASCE and the States of California and New York have formed committees to develop such standards.[115]

Other sectors of government and industry are also starting to consider climate risk a major systemic risk. In its 2018 Global Risks Report, the World Economic Forum listed the top five environmental risks—including extreme weather events and temperatures and failures of climate change mitigation and adaptation—in terms of both likelihood and the impact on the global economy.[116] The U.S. military now routinely integrates climate risks into its analysis, plans, and programs,[117] with particular attention paid to climate effects on force readiness, military bases, and training ranges (Ch. 16: International, KM 3).[118,119] Naval Station Norfolk, for example, has replaced existing piers with double-decker piers that are elevated by several more feet and thus more resilient to rising sea levels and extreme weather events (Ch. 1: Overview, Figure 1.8).

Overcoming Up-Front Challenges

While yielding benefits, adaptation also presents challenges. These include difficulties obtaining the necessary funds; insufficient information and relevant expertise; jurisdictional mismatches among those responsible for taking adaptation actions and those who benefit from those actions; conflicting interests among relevant parties; and the pressures on agencies and professionals that serve the public to act cautiously, in particular by seeking to follow long-established procedures and experience.

Insufficient funding often hinders adaptation (Ch. 8: Coastal; Ch. 15: Tribes).[120,121,122] At the local level, adaptation planning and assessment have been supported by a mix of local government funds and federal, state, and foundation grants.[121] Full-scale implementation of the proposals resulting from these adaptation planning and assessment activities would require significantly more resources. In principle, the potential for longer-term savings can be used to generate near-term financing for adaptation efforts. But the mechanisms for doing so are not yet widely in place. Underwriters of municipal bonds, the most common means of financing water infrastructure in the United States, are just beginning to incorporate requirements for long-term sustainability under a changing climate as a condition for going to market.[112]

To the extent that climate resilience becomes an expected and required attribute of decisions concerning infrastructure and other long-term investments, as well as an expected part of asset management and life-cycle cost estimates, financing should become more available for cost-effective adaptation actions.[123] Changing social and economic norms could also affect the availability of financing. Once the implications become widely understood, public expectations, professional standards, and due diligence on the part of financers may similarly discourage investing in long-lived infrastructure designed for stationary conditions, as opposed to currently changing and future climate conditions.[124]

Adaptation often increases up-front costs, thus increasing the salience of steps to reduce those costs. Federal, state, and local governments in the United States spend over $400 billion annually on public infrastructure.[125] Estimates of annual adaptation costs range from tens to hundreds of billions of dollars annually.[78] Taking advantage of new infrastructure investments and capital stock turnover provides one particularly favorable opportunity for low-cost, proactive adaptation in both the public and private sectors.[2] Many jurisdictions and businesses possess significant stocks of deteriorating transportation, water, energy, housing, and other infrastructure, which often already lack resilience to current climate and weather events (Ch. 3: Water; Ch. 4: Energy; Ch. 12: Transportation).[3,126,127] The expected turnover of this capital stock creates opportunities for adaptation but also raises challenges, such as equity concerns, if, for example, upgrading the resilience of housing stock makes it unaffordable for lower-income residents.

Flexible design and adaptive planning can also reduce near-term adaptation costs while keeping options open for future resilience.[128] Such options begin with low-regret options, invest in capacity building, and adjust over time to new information. The Fort Pulaski example cited previously included a new coastal protection structure with an adaptive design that can be inexpensively adjusted as the future risk grows larger. The Metropolitan Water District of Southern California uses adaptive management to organize its 25-year Integrated Resource Plan; factored into its near-term investments in local supplies is the expectation that some investments will be expanded and others reduced as climate, demand, regulatory, and other conditions change in the future.[129] However, explicitly signaling that policies will change in the future may impede enforcement, make decision-makers seem indecisive, and make it easier for them to succumb to political pressure from special interests.[130]

Catalysts for Adaptation

Catalytic events, external incentives, community interest, leadership, and outside funding all help spur adaptation planning and implementation. Catalytic events, including disasters caused by extreme storms or droughts, often precipitate or accelerate adaptation action,[131,132] as happened with Superstorm Sandy in 2012, Hurricane Katrina in 2005, and the 2011–2016 drought in California (see, for example, Ch. 25: Southwest).

Internal drivers of adaptation include political leadership and policy entrepreneurs.[103] In addition, a recognition of the challenges posed by climate change and an ability to integrate the problem and potential solutions into existing belief and value structures also provide important catalysts for adaptation.

External incentives include the legal requirements, engineering standards, climate-related financial risk disclosure requirements, and changes in insurance coverage. For instance, some existing laws and regulations provide catalysts for adaptation,[133] typically through procedural planning requirements rather than substantive mandates. At the state and local levels, some laws specifically require the consideration of climate change impacts and adaptation options in planning processes, but these cover only a small subset of jurisdictions and geographic areas in the United States.[134,135,136] At the federal level, few laws explicitly promote adaptation, but many can be interpreted as requiring the consideration of climate change impacts on the ability of a federal agency to comply with various statutory and regulatory mandates.[23,137]

Once begun, successful adaptation often entails sustained networks, financing, the sharing of best practices, and champions, as shown in Box 28.3.

Box 28.3: Common Attributes of Effective Adaptation

Factors that shape or contribute to the successful adoption and implementation of adaptation by public-sector organizations include

- plans written by a professional staff and approved by elected officials;
- community engagement, including the participatory development of plans; the formation of action teams or regional collaborations[138] across jurisdictions, sectors, and scales; and public- and private-sector leaders who champion and support the process;
- adaptation actions that address multiple community goals, not just climate change;
- well-structured implementation, including the identification of parties responsible for each step, explicit timelines, explicit and measurable goals, and explicit provisions and timelines for monitoring and updating the plan; and
- adequate funding for the adaptation actions and for sustained community outreach and deliberation.

(Adapted from Brody and Highfield 2005, Berke et al. 2012, Horney et al. 2012, IPCC 2012, NRC 2009, Cutter et. al. 2012, GAO 2016, Wilhite and Pulwarty 2017, Bassett and Shandas 2010, Berke and Lyles 2013, Lyle and Stevens 2014, Hughes 2015, Highfield and Brody 2012, Mimura et al. 2014[47,60,70,139,140,141,142,143,144,145,146,147,148,149].)

Formal and informal networks of government, nongovernmental organizations, and academic, faith-based, and private-sector parties engaged in developing and implementing adaptation are expanding. These networks support individuals, communities, and organizations as they strive to understand and reduce current and future climate risks. Federal, state, and local agencies; nongovernmental organizations; utilities and industry associations; and private-sector consultants have in recent years developed a wide range of written guidance and online platforms intended to support climate adaptation planning and mainstreaming efforts. While not exhaustive, the list includes the 100 Resilient Cities, the C40 Cities Climate Leadership Group, the Urban Sustainability Directors Network (USDN), and the Water Utility Climate Alliance.

Over the past several years, examples of sustained collaborative partnerships between research and management in support of climate risk management have included NOAA's Regional Integrated Sciences and Assessments (RISA), the U.S. Department of Agriculture's (USDA) Climate Hubs, and the Department of the Interior's (DOI) Climate Adaptation Science Centers (CASCs). These regional climate information networks provide data, tools, forecasts, interpretation, and extension services for agencies and communities to build into integrated services and work together to coordinate stakeholder engagement across multiple sectors as new knowledge emerges.[150,151] Some examples include knowledge platforms, such as the Climate Adaptation Knowledge Exchange (www.cakex.org), the Georgetown Climate Center's Adaptation Clearinghouse (http://www.adaptationclearinghouse.org/), and the U.S. Climate Resilience Toolkit website (toolkit.climate.gov); these platforms include directories of practitioners and inventories of data tools for managing natural and built systems in the face of climate change. More local, targeted resources, such as Louisiana's Coastal Protection Restoration Authority Master Plan Data Viewer (http://cims.coastal.la.gov/masterplan/), offer detailed information about climate risks and probabilities in specific geographic locations to help planners and communities better anticipate and prepare for climate impacts. Such initiatives and networks enable practitioners to share best practices and evaluate and inform adaptation implementation while empowering communities to advance preparedness and resilience efforts across the United States.

Beyond Incremental Change

Integrating climate risk into existing practices can lead to change that is more than incremental. For instance, it often proves profitable in the near term to build in low-lying areas subject to future extreme flooding[152] rather than in areas with lower future risk. Updated flood maps and risk-adjusted insurance rates would likely lead to different patterns of development.[153] In many cases, however, addressing the full range of future climate change requires substantial changes in organizational practices and procedures, in public- and private-sector institutions, in individual and societal expectations and norms, in capital investment planning, and in laws.[154,155] Decision-makers may wish to take active steps to anticipate and steer change in desired directions and to avoid the unanticipated consequences of ad hoc or crisis-based responses. In some cases, this involves seeking, legitimizing, and accelerating large changes, rather than attempting to retain today's conditions as long as possible.[10,156,157]

Reducing climate risk often requires managing interdependent systems in ways that transcend current jurisdictional and sectoral boundaries (Ch. 4: Energy; Ch. 17: Complex Systems, KM 3). Water, electric power supply, and agriculture often depend critically on one another (see Ch. 17: Complex Systems, KM 1) but are not treated similarly for potential adaptation actions. Effective climate risk management often requires closer coordination among regulatory agencies and, in some cases, may necessitate some restructuring. For instance, the City of Los Angeles's One Water LA program requires multiple city agencies to coordinate on integrated management of the city's water, land-use, and flood control actions.[158] Major reforms can prove difficult and often occur only in response to major system shocks, such as reforms to the Stafford Act after Hurricane Katrina[159,160,161] or the consolidation of many local water agencies in Australia into a small number of large, regional organizations during a decade of severe drought.[162]

Some sectors are already taking actions that go beyond integrating climate risk into current practices. Faced with substantial climate-induced future changes, including new invasive species and shifting ranges, ecosystem managers have already begun to adopt novel approaches, such as assisted migration and wildlife corridors (Ch. 7: Ecosystems, KM 2), and to rethink the goals of conservation management.[163] Many millions of Americans live in coastal areas threatened by sea level rise; in all but the very lowest sea level rise projections, retreat will become an unavoidable option in some areas of the U.S. coastline (Ch. 8: Coastal, KM 1). The Federal Government has already provided resources for the relocation of some communities, such as the Biloxi-Chitimacha-Choctaw tribe from Isle de Jean Charles in Louisiana. But the potential need for millions of people and billions of dollars of coastal infrastructure to be relocated in the future creates challenging legal, financial, and equity issues that have not yet been addressed.

The ability of adaptation to reduce severe climate impacts like these will ultimately depend less on scientific uncertainties and the ability to implement engineering solutions than on perceived loss of culture and identity, in particular identities associated with unique cultural heritage sites and a sense of place (Ch. 8: Coastal; Ch. 15: Tribes, KM 2).[68] Because different regions and groups face different levels of risk and have differing abilities to respond, considerations of equity and justice influence judgments about any limits to adaptation.[52,68]

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Traceable Accounts

Process Description

The scope for this chapter was determined by the Fourth National Climate Assessment (NCA4) Federal Steering Committee, which is made up of representatives from the U.S. Global Change Research Program member agencies. The scope was also informed by research needs identified in the Third National Climate Assessment (NCA3). Authors for this NCA4 chapter were selected to represent a range of public- and private-sector perspectives and experiences relevant to adaptation planning and implementation.

This chapter was developed through technical discussions of relevant evidence and expert deliberation by chapter authors during teleconferences, e-mail exchanges, and a day-long in-person meeting. These discussions were informed by a comprehensive literature review of the evidence base for the current state of adaptation in the United States. The author team obtained input from outside experts in several important areas to supplement its expertise.

Key Message 1

Adaptation Implementation Is Increasing

Adaptation planning and implementation activities are occurring across the United States in the public, private, and nonprofit sectors. Since the Third National Climate Assessment, implementation has increased but is not yet commonplace. (*High Confidence*)

Description of evidence base

There exists extensive documentation in the gray literature of specific adaptation planning and implementation activities underway by local, state, regional, and federal agencies and jurisdictions. The literature also contains reports that attempt to provide an overview of these activities, such as the recent set of case studies in Vogel et. al. (2017).[14] Websites, such as those of the Georgetown Climate Center (http://www.georgetownclimate.org), provide summaries and examples of adaptation activities in the United States. The sectoral and regional chapters in this National Climate Assessment also provide numerous examples of adaptation planning and implementation activities. The literature also offers work that aims to provide surveys of large numbers of adaptation activity, such as Moser et. al. (2018)[121] and Stults and Woodruff (2016).[164]

Major uncertainties

While the amount of adaptation-related activity is clearly increasing, the lack of clear standards and the diverse lexicon used in different sectors make it difficult to systematically compare different adaptation activities at the level of outcomes across sectors and regions of the country. In addition, publicly available adaptation plans may never actually result in implementation. It is thus difficult to provide a quantitative assessment of the increase in adaptation activity other than just counting plans and initiatives. Given the reliance on small-sample surveys, judgments about the distribution of adaptation actions across categories have potentially large errors that are difficult to estimate. In addition, it is difficult to assess the contribution of these activities to concrete outcomes such as risk reduction or current and future improvements to well-being, security, and environmental protection.[130] There also exists little gap analysis that compares any given set of adaptation activities with what might be appropriate according to some normative standard or what might be reasonably achieved. Thus, while adaptation activities are clearly increasing in the United States, scant evidence exists for judging their consequences.

Description of confidence and likelihood

There is *high confidence* that the amount of adaptation activity, in particular implementation activity, is increasing. There is less agreement and evidence regarding the consequences of this activity.

Key Message 2

Climate Change Outpaces Adaptation Planning

Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past. Incorporating information on current and future climate conditions into design guidelines, standards, policies, and practices would reduce risk and adverse impacts. (*High Confidence*)

Description of evidence base

The assumption that the historical record of events and variability will be the same in the future is called the stationarity assumption[27] and has guided planning for climate and weather events in most places for most of recorded history. The evidence is strong that the stationarity assumption is no longer valid for all impacts and variability in all locations, because climate change is altering both the events and their variability.[3,4,28,165] Regional chapters in this assessment establish the climate variables for which, and the extent to which, non-stationarity has been confirmed around the United States. These chapters also provide extensive documentation of cases in which failure to adapt to current and future climate conditions can cause significant adverse impacts.

Major uncertainties

While significant uncertainties can exist in estimating the extent to which current variability differs from historic observations in any particular location, there is robust evidence that such differences do occur in many locations (see Ch. 18: Northeast; Ch. 19: Southeast; Ch. 20: U.S.Caribbean; Ch. 21: Midwest; Ch. 22: N. Great Plains; Ch. 23: S. Great Plains; Ch. 24: Northwest; Ch. 25: Southwest; Ch. 26: Alaska; and Ch. 27: Hawaiʻi & Pacific Islands).[5,6,28,166] However, the development and use of analytic tools, decision-making processes, and application mechanisms built on the assumption of non-stationarity lag significantly behind the growing realization that stationarity is no longer a sound basis for long-range planning.[167] Nonetheless, new techniques are being applied.[10,72,168] For example, scenario planning can provide alternative actions that can be carried out if different impacts occur.[70,71]

Description of confidence and likelihood

There is *high confidence* that most organizations' planning is currently based on extensions from the record of local climate conditions.[169]

Key Message 3

Adaptation Entails Iterative Risk Management

Adaptation entails a continuing risk management process; it does not have an end point. With this approach, individuals and organizations of all types assess risks and vulnerabilities from climate and other drivers of change (such as economic, environmental, and societal), take actions to reduce those risks, and learn over time. (*High Confidence*)

Description of evidence base

Evidence from a large body of literature and observations of experience support the judgment that iterative risk management is a useful framework (e.g., National Research Council 2009, America's Climate Choices 2010, Kunreuther et al. 2012[142,170,171]). The literature also suggests its conceptual similarity with other methods that use different names.

Major uncertainties

The literature and practice of climate change are undergoing a process of maturation and convergence. The process began with many organizations and sectors developing their own approaches and terminology in response to climate risks, meaning that a wide variety of approaches still exist in the field. We believe that the field will progress and converge on the most effective approaches, including iterative risk management. But this convergence is still in process, and the outcome remains uncertain.

Description of confidence and likelihood

Significant agreement and strong evidence provide *high confidence* that adaptation is a form of iterative risk management and that this is an appropriate framework for understanding, addressing, and communicating climate-related risks.[33]

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term (*medium confidence*). Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security (*high confidence*).

Description of evidence base

Both limited field applications and literature reviews highlight adaptation co-benefits, including those associated with equity considerations.[83] Near-term benefits are assessed from observations of adaptation results, as well as from comparisons to similar situations without such responses; longer-term benefits are generally assessed from projections.

Major uncertainties

Benefits are based on understanding the relevant systems so that one can compare similar cases and construct counterfactuals. Such understanding is excellent for many engineered systems (for example, how a storm drain performs under various rainfall scenarios) but is less robust for many biological systems. Benefit–cost ratios can have large uncertainties associated with estimates of costs, the projection of benefits, and the economic valuation of benefits. In addition, because expected differences in benefit–cost ratios are sufficiently large and the number of current examples is sufficiently low, there are large uncertainties in applying results from one case to another.

Description of confidence and likelihood

There is suggestive evidence that provides *medium confidence* that many proactive adaptation actions offer significant benefits that exceed their costs. However, because of a small sample size and insufficient evaluation, it is in general hard to know the extent to which this is true in any particular case. There is strong agreement that evaluating adaptation involves consideration of a wide range of measures of social well-being.

Key Message 5

New Approaches Can Further Reduce Risk

> Integrating climate considerations into existing organizational and sectoral policies and practices provides adaptation benefits. Further reduction of the risks from climate change can be achieved by new approaches that create conditions for altering regulatory and policy environments, cultural and community resources, economic and financial systems, technology applications, and ecosystems. (*High Confidence*)

Description of evidence base

There is significant agreement, but only case study evidence, that effective adaptation can be realized by mainstreaming.[100,101,102] Significant evidence exists regarding the scale of longer-term adaptation required in some climate futures based on modeling studies. Significant agreement, but less direct evidence, exists on the scale of organizational and other changes needed to implement these adaptation actions.

Major uncertainties

It is not well understood how community acceptance of needed adaptations develops. This presents both a barrier to the implementation of adaptation measures and an opportunity for additional research into ways to close this gap in understanding. Additionally, a need exists to clarify the co-benefits of addressing multiple threats and opportunities. Effective adaptation also depends on networks of collaboration among researchers and practitioners and the long-term support of monitoring networks. The sustainability of both types of networks is a major uncertainty. Their effectiveness is both an uncertainty and major research need.

Description of confidence and likelihood

There is significant agreement that provides *high confidence*, in at least some cases, that both 1) mainstreaming climate information into existing risk management and 2) creating enabling environments and institutions to improve adaptation capacity, implementation, and evaluation reduce risk, produce co-benefits across communities and sectors, and help secure economic investments into the future.

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29 Reducing Risks Through Emissions Mitigation

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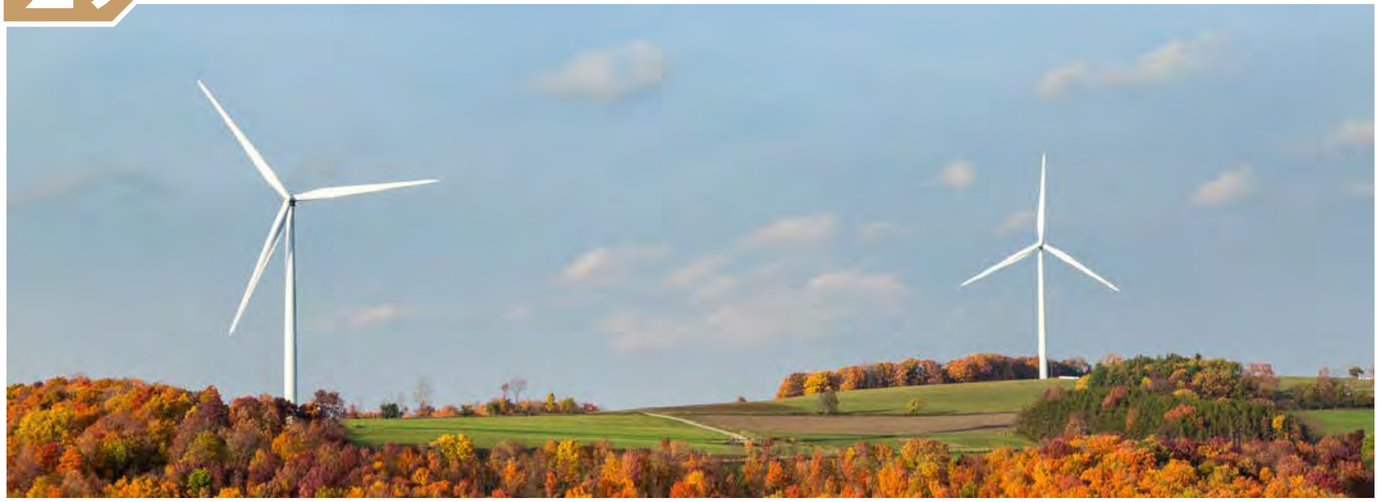
29 Reducing Risks Through Emissions Mitigation



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Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector. Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions.

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century. It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent.

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region. The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences. Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors. This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable.

Executive Summary

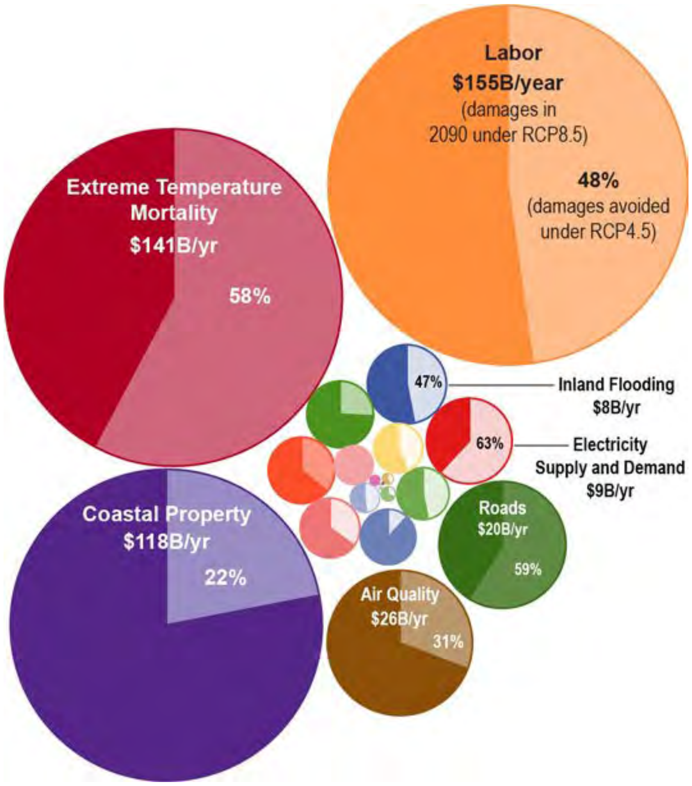
Current and future emissions of greenhouse gases, and thus emission mitigation actions, are crucial for determining future risks and impacts of climate change to society. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those reductions, and the relative mix of mitigation strategies for emissions of long-lived greenhouse gases (namely, carbon dioxide), short-lived greenhouse gases (such as methane), and land-based biologic carbon.[1] Many actions at national, regional, and local scales are underway to reduce greenhouse gas emissions, including efforts in the private sector.

Climate change is projected to significantly damage human health, the economy, and the environment in the United States, particularly under a future with high greenhouse gas emissions. A collection of frontier research initiatives is underway to improve understanding and quantification of climate impacts. These studies have been designed across a variety of sectoral and spatial scales and feature the use of internally consistent climate and socioeconomic scenarios. Recent findings from these multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly at the end of the century—with negative consequences for a large majority of sectors, including infrastructure and human health.[2,3,4,5] For sectors where positive effects are observed in some regions or for specific time periods, the effects are typically dwarfed by changes happening overall within the sector or at broader scales.

Recent studies also show that many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions. While the difference in climate outcomes between scenarios is more modest through the first half of the century,[6] the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter. Research supports that early and substantial mitigation offers a greater chance of avoiding increasingly adverse impacts.

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population. Physical damages to coastal property and transportation infrastructure are particularly sensitive to adaptation assumptions, with proactive measures estimated to be capable of reducing damages by large fractions. Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and adaptation activities can be considered complementary strategies. However, adaptation can require large up-front costs and long-term commitments for maintenance, and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk. Interactions between adaptation and mitigation strategies can result in benefits or adverse consequences. While uncertainties still remain, advancements in the modeling of climate and economic impacts, including current understanding of adaptation pathways, are increasingly providing new capabilities to understand and quantify future effects.

Projected Damages and Potential for Risk Reduction by Sector



	Annual Economic Damages in 2090		
	Sector	**Annual damages under RCP8.5**	**Damages avoided under RCP4.5**
🟧	**Labor**	$155B	48%
🟥	**Extreme Temperature Mortality◊**	$141B	58%
🟪	**Coastal Property◊**	$118B	22%
🟫	**Air Quality**	$26B	31%
🟩	**Roads◊**	$20B	59%
🟥	**Electricity Supply and Demand**	$9B	63%
🟦	**Inland Flooding**	$8B	47%
🟩	**Urban Drainage**	$6B	26%
🟥	**Rail◊**	$6B	36%
🟥	**Water Quality**	$5B	35%
🟦	**Coral Reefs**	$4B	12%
🟩	**West Nile Virus**	$3B	47%
🟨	**Freshwater Fish**	$3B	44%
🟥	**Winter Recreation**	$2B	107%
🟦	**Bridges**	$1B	48%
🟩	**Munic. and Industrial Water Supply**	$316M	33%
🟨	**Harmful Algal Blooms**	$199M	45%
🟪	**Alaska Infrastructure◊**	$174M	53%
⬜	**Shellfish***	$23M	57%
🟩	**Agriculture***	$12M	11%
⬛	**Aeroallergens***	$1M	57%
⬛	**Wildfire**	−$106M	−134%

The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.[2] Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. *From Figure 29.2 (Source: adapted from EPA 2017).*[2]

Introduction

This chapter assesses recent advances in climate science and impacts, adaptation, and vulnerability research that have improved understanding of how potential mitigation pathways can avoid or reduce the long-term risks of climate change within the United States. This chapter does not evaluate technology options, costs, or the adequacy of existing or planned mitigation efforts relative to meeting specific policy targets, as those topics have been the subject of domestic (e.g., Executive Office of the President 2016, CCSP 2007, DeAngelo et al. 2017, NRC 2015[7,8,9,10]) and international analyses (e.g., Fawcett et al. 2015, Clarke et al. 2014[11,12]). Also, this chapter does not assess the potential roles for carbon sinks (or storage) in mitigation, which are discussed in Chapter 5: Land Changes, and in the Second State of the Carbon Cycle Report.[13] Further, it is beyond the scope of this chapter and this assessment to evaluate or recommend policy options.

USGCRP defines risk as threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).

Both mitigation and adaptation responses to climate change are likely to occur as part of an iterative risk management strategy in which initial actions are modified over time as learning occurs (Ch. 28: Adaptation). This chapter focuses primarily on the early stages of this iterative process in which risks and vulnerabilities are identified and the potential climate impacts of emissions scenarios are assessed.

Box 29.1: Options for Reducing or Removing Greenhouse Gases

Mitigation refers to measures to reduce the amount and speed of future climate change by reducing emissions of greenhouse gases (GHGs) or by increasing their removal from the atmosphere. Emission reduction measures include replacing conventional, CO_2-emitting fossil fuel energy technologies or systems with low- or zero-emissions ones (such as wind, solar, nuclear, biofuels, fossil energy with carbon capture and storage, and energy efficiency measures), as well as changing technologies and practices in order to lower emissions of other GHGs such as methane, nitrous oxide, and hydrofluorocarbons.[7,14,15] Measures that enhance the removal of CO_2 from the atmosphere (see Box 29.3) include changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO_2 through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO_2.[16] Using captured CO_2 in products such as polymers and cement is a potential alternative to geologic storage.[17]

The adoption of these measures may be promoted through a variety of policy instruments, such as emissions pricing (that is, GHG emission fees or emissions caps with permit trading), regulations and standards (such as emission standards, technology requirements, and building codes), subsidies (for example, tax incentives and rebates), and public funding for research, development, and demonstration programs.

Timing and Magnitude of Action

Current and future emissions, and thus emissions mitigation actions, are crucial for determining future risks and impacts. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those emissions reductions, and the relative mix of mitigation strategies for emissions of long-lived GHGs (namely, CO_2), short-lived GHGs (such as methane), and land-based biologic carbon.[1] Intentional removal of CO_2 from the atmosphere, often referred to as negative emissions, or other climate interventions have also been proposed[10,18] and may play a role in future mitigation strategies (see Box 29.3).

Net cumulative CO_2 emissions in the industrial era will largely determine long-term global average temperature change[9] and thus the risks and impacts associated with that change in the climate. Large reductions in present-day emissions of the long-lived GHGs are estimated to have modest temperature effects in the near term (over the next couple decades), but these emission reductions are necessary to achieve any long-term objective of preventing warming of any desired magnitude.[9] Decisions that decrease or increase emissions over the next few decades will set into motion the degree of impacts that will likely last throughout the rest of this century, with some impacts (such as sea level rise) lasting for thousands of years or even longer.[19,20,21]

Meeting any climate stabilization goal, such as the oft-cited objective of limiting the long-term globally averaged temperature to 2°C (3.6°F) above preindustrial levels, necessitates that there be a physical upper limit on the cumulative amount of CO_2 that can be added to the atmosphere.[9] Early and substantial mitigation offers a greater chance for achieving a long-term goal, whereas delayed and potentially much steeper emissions reductions jeopardize achieving any long-term goal given uncertainties in the physical response of the climate system to changing atmospheric CO_2, mitigation deployment uncertainties, and the potential for abrupt consequences.[11,22,23] Early efforts also enable an iterative approach to risk management, allowing stakeholders to respond to what is learned over time about climate impacts and the effectiveness of available actions (Ch. 28: Adaptation).[24,25,26] Evidence exists that early mitigation can reduce climate impacts in the nearer term (such as reducing the loss of perennial sea ice and effects on ice-dwelling species) and, in the longer term, prevent critical thresholds from being crossed (such as marine ice sheet instability and the resulting consequences for global sea level change).[27,28,29,30]

State of Emissions Mitigation Efforts

Actions are currently underway at global, national, and subnational scales to reduce GHG emissions. This section provides an overview of agreements, policies, and actions being taken at various levels.

Long-Term Temperature Goals and the Paris Agreement

The idea of limiting globally averaged warming to a specific value has long been examined in the scientific literature and, in turn, gained attention in policy discourse (see DeAngelo et al. 2017 for additional information[9]). Most recently, the Paris Agreement of 2015 took on the long-term aims of "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".[31] These targets were developed with the goal of avoiding the most severe climate impacts; however, they should not be viewed as thresholds below which there are zero risks and above which numerous tipping points occur (that is, a point at which a change in the climate triggers a significant environmental event, which may be permanent). In order to reach the Paris Agreement's long-term temperature goal, Parties to the Agreement "aim to reach global peaking of GHG emissions as soon as possible . . . and to undertake rapid reductions thereafter." Many countries announced voluntary, nonbinding GHG emissions reduction targets and related actions in the lead-up to the Paris meeting; these announcements addressed emissions through 2025 or 2030 and took a range of forms.[31] The Paris Agreement has been ratified by 180 Parties to the UN Framework Convention on Climate Change, which account for 88% of global GHG emissions.[32,33]

Achieving the Paris Agreement target of limiting global mean temperature to less than 2°C (3.6°F) above preindustrial levels requires substantial reductions in net global CO_2 emissions prior to 2040 relative to present-day values and likely requires net CO_2 emissions to become zero or possibly negative later in the century, relying on as-yet unproven technologies to remove CO_2 from the atmosphere. To remain under this temperature threshold with two-thirds likelihood, future cumulative net CO_2 emissions would need to be limited to approximately 230 gigatons of carbon (GtC), an amount that would be reached in roughly the next two decades assuming global emissions follow the range between the RCP4.5 and RCP8.5 scenarios.[9] Achieving global GHG emissions reduction targets and actions announced by governments in the lead-up to the 2015 Paris climate conference would hold open the possibility of meeting the 2°C (3.6°F) temperature goal, whereas there would be virtually no chance if net global emissions followed a pathway well above those implied by country announcements.[9]

In June 2017, the United States announced its intent to withdraw from the Paris Agreement.[34] The statement is available online: https://www.whitehouse.gov/briefings-statements/statement-president-trump-paris-climate-accord/. The earliest effective date of formal withdrawal is November 4, 2020. Some state governments, local governments, and private-sector entities have announced pledges to reduce emissions in the context of long-term temperature aims consistent with those outlined in the Paris Agreement.[35,36]

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector. Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions.

Many activities within the public and private sectors either aim to or have the effect of reducing these emissions. Fossil fuel combustion accounts for 77% of the total U.S. GHG emissions (using the 100-year global warming potential), with agriculture, industrial processes, and methane from fossil fuel extraction and processing as well as waste accounting for the remainder.[37] A 100-year global warming potential is an index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over one hundred years, relative to that of the reference substance, CO_2.[38] At the federal level, a number of measures have been implemented to promote advanced, low-carbon energy technologies and fuels, including energy efficiency. Broadly considered, these measures include

GHG regulations; other rules and regulations with climate co-benefits; codes and standards; research, development, and demonstration projects and programs; federal procurement practices; voluntary programs; and various subsidies (such as production and investment tax credits).[14,39] Federal measures to address sources other than fossil fuel combustion include agriculture and forestry programs to increase soil and forest carbon sequestration and minimize losses through wildfire or other land-use processes, regulations to phase down hydrofluorocarbons, and standards for reducing methane emissions from fossil fuel extraction and processing.[14] The Administration is currently reviewing many of these measures through the lens of Executive Order 13783, which aims to ease regulatory burdens on "the development or use of domestically produced energy resources, with particular attention to oil, natural gas, coal, and nuclear energy resources."[40]

State, local, and tribal government mitigation approaches include comprehensive emissions reduction strategies as well as sector- and technology-specific policies designed for many reasons. As shown in Figure 29.1a, at least 455 cities support emissions reductions in the context of global efforts, including 110 with emissions reduction targets.[36] At the state level, the color shown on each state indicates the total number of activities taken in that state across six policy areas: GHG target/cap/pricing; renewable/carbon dioxide capture and storage (CCS)/nuclear; transportation; energy efficiency; non-CO_2 GHG; and forestry and land use.[36] Figure 29.1b shows the number of activities by policy area for each state. For example, states in the Northeast take part in the Regional Greenhouse Gas Initiative, a mandatory market-based effort to reduce power sector emissions.[41] California has a legal mandate to reduce emissions 40% below 1990 levels by 2030, and in a 2017 law, the state extended its emissions trading program to 2030, as well. Several states have adopted voluntary pledges to reduce emissions. Technology-specific approaches include targets to increase the use of renewable energy such as wind and solar, zero- or low-emissions transportation options, and energy efficient technologies and practices.[42,43] Many tribes are also prioritizing energy-efficiency and renewable-energy projects (Ch. 15: Tribes, KM 1).[44] Mitigation activities related to methane and forestry/land-use activities are growing in number and vary by locale.

In the private sector, many companies seek to provide environmental benefits for a variety of reasons, including supporting environmental stewardship, responding to investor demands for prudent risk management, finding economic opportunities in efforts to reduce GHG emissions, and, in the case of multinationals, meeting mitigation mandates in the European Union or other jurisdictions. Since the last National Climate Assessment, private companies have increasingly taken inventory of their emissions and moved forward to implement science-based emissions reduction targets as well as internal carbon prices.[36] The Carbon Disclosure Project[46] is one example of a voluntary program where companies register their pledges to reduce GHG emissions and/or to manage their climate risks. Corporate purchases of and commitments to purchase renewable energy have increased over the last decade.[47]

Mitigation-Related Activities at State and Local Levels

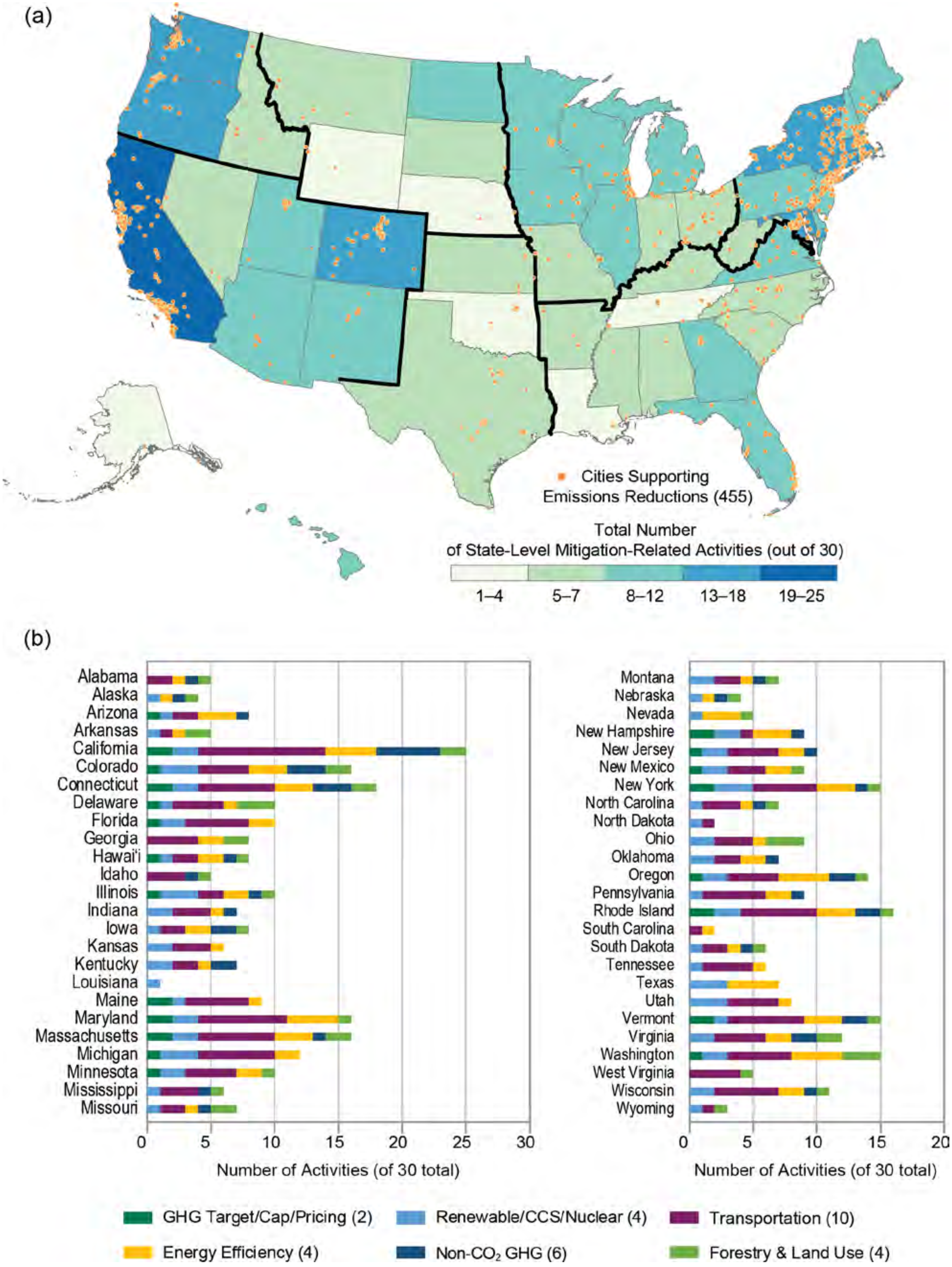


Figure 29.1: The map (a) shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; the chart (b) depicts the type and number of activities by state.[36] Several territories also have a variety of mitigation-related activities including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands.[42,45] Sources: (a) EPA and ERT, Inc.; (b) adapted from America's Pledge 2017.[36]

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. GHG emissions over the past decade. In 2016, U.S. emissions were at their lowest levels since 1994.[37] Power sector emissions were 25% below 2005 levels in 2016, the largest sectoral reduction over this time.[37] This decline was in large part due to increases in natural gas generation as well as renewable energy generation and energy efficiency (Ch. 4: Energy, KM 2).[48] Given these changes in the power sector, the transportation sector currently has the largest annual sectoral emissions (Ch. 12: Transportation). As of the writing of this report, projections of U.S. fossil fuel CO_2 and other GHG emissions show flat or declining trajectories over the next decade, with a central estimate of about 15%–20% below 2005 levels by 2025.[49,50] Prior to the adoption of the Paris Agreement, the United States put forward a nonbinding "intended nationally determined contribution" of reducing emissions 26%–28% below 2005 levels in 2025. On June 1, 2017, President Trump announced that the United States would cease implementation of this nationally determined contribution. Some state and local governments, as well as private-sector entities, have announced emission reduction pledges which aim to be consistent with the nonbinding target.[35,36] For more information on trends in, drivers of, and potential efforts to address U.S. GHG emissions, see the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[37]

Reducing Impacts Through Mitigation

To understand how large-scale emissions mitigation can reduce climate impacts, it is useful to look at how the impacts change under various emissions scenarios. In recent years, the science and economics of estimating future climate change impacts have advanced substantially, with increasing emphasis on interdisciplinary approaches to investigate impacts, vulnerabilities, and responses.[51,52,53] These advances have enabled several ongoing frontier research initiatives to improve understanding and quantification of climate impacts at various spatial scales ranging from global to local levels. This section describes findings for the United States from a selection of recent multisector coordinated modeling frameworks listed in Table 29.1, which are frequently cited throughout this chapter because each report provides modeling results across multiple sectors and scenarios similar to those developed for this report. These approaches commonly feature the use of internally consistent climate and socioeconomic scenarios and underlying assumptions across a variety of sectoral analyses. While research projecting physical and economic impacts in the United States has increased considerably since the Third National Climate Assessment (NCA3), it is important to note that this literature is incomplete in its coverage of the breadth of potential impacts.

Collaboration or Project Name	Host/Lead Organization and References	Sectors Covered	Coverage
Benefits of Reduced Anthropogenic Climate changE (BRACE)	National Center for Atmospheric Research (O'Neill et al. 2017)[4]	Heat extremes and health, agriculture and land use, tropical cyclones, sea level rise, drought and conflict	Global
Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth (CIRCLE)	Organisation for Economic Co-operation and Development (OECD 2015)[55]	Tourism, agriculture, coastal, energy, extreme precipitation events, health	Global
Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)	Potsdam Institute for Climate Impact Research (Huber et al. 2014)[56]	Water, agriculture, biomes, infrastructure, health/malaria, fishery, permafrost	Global
American Climate Prospectus (ACP)	Climate Impact Lab (Houser et al. 2015; Hsiang et al. 2017)[3,5]	Agriculture, health, labor productivity, crime and conflict, coastal, energy	United States
Climate Change Impacts and Risk Analysis (CIRA)	U.S. Environmental Protection Agency (EPA 2015, 2017)[2,57]	More than 20 specific impacts categorized into 6 broad sectors: health (including labor productivity), infrastructure, electricity, water resources, agriculture, ecosystems	United States
California Climate Change Assessments	State of California (Cayan et al. 2008, 2013; California Energy Commission 2006)[58,59,60]	Public health, agriculture, energy, coastal, water resources, ecosystems, wildfire, recreation	State-Level
Colorado Climate Change Vulnerability Study	Colorado Energy Office (Gordon and Ojima 2015)[61]	Ecosystems, water, agriculture, energy, transportation, recreation and tourism, public health	State-Level
New York ClimAID Project	New York State Energy Research and Development Authority (Rosenzweig et al. 2011; Horton et al. 2014)[62,63]	Water resources, coastal zones, ecosystems, agriculture, energy, transportation, telecommunications, public health	State-Level

Table 29.1: Selection of Multisector Impacts Modeling Frameworks Since NCA3. Source: adapted from Diaz and Moore 2017.[54]

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century. It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent.

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high GHG emissions, such as RCP8.5, and under scenarios with limited or no adaptation (for more on RCPs, see the Scenario Products section of App. 3).[64] Recent findings from multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly towards the end of the century—with negative consequences for a large majority of sectors. Moreover, the impacts and costs of climate change are already being felt in the United States, and recent extreme weather and climate-related events can now be attributed with increasingly higher confidence to human-caused warming.[65] Impacts associated with human health, such as premature mortality due to extreme temperature and poor air quality, are commonly some of the most economically substantial (Ch. 13: Air Quality; Ch. 14: Human Health).[2,3,4,5] While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources.[66,67] Further, some impacts will very likely be irreversible for thousands of years, including those to species, such as corals (Ch. 9: Oceans; Ch. 27: Hawai‘i & Pacific Islands),[1,2,68] or those that involve the exceedance of thresholds, such as the effects of ice sheet disintegration on accelerated sea level rise, leading to widespread effects on coastal development lasting thousands of years.[69,70,71] Figure 29.2 shows that climate change is projected to cause damage across nearly all of the sectors analyzed. The conclusion that climate change is projected to result in adverse impacts across most sectors is consistently found in U.S.-focused multisector impact analyses.[2,3,4,5] For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).[2,3,4,5]

Projected Damages and Potential for Risk Reduction by Sector

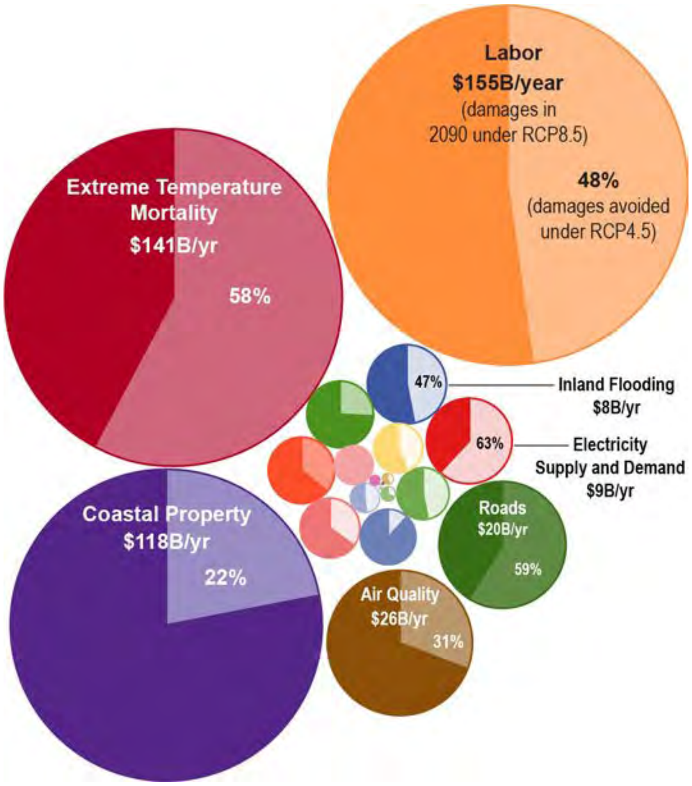


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Figure 29.2: The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.[2] Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. Source: adapted from EPA 2017.[2]

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Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region. The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter.

Many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in GHG emissions (Figure 29.2). While the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,[6] the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter.[2,3,4] For some sectors, this creates large projected benefits of mitigation. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (overall) thousands to tens of thousands of deaths per year from extreme temperatures (Ch. 14: Human Health),[2,3,5] hundreds to thousands of deaths per year from poor air quality (Ch. 13: Air Quality),[2,72] and the annual loss of hundreds of millions of labor hours from extreme temperatures.[2,3] When monetized, each of these avoided health impacts represents domestic economic benefits of mitigation on the order of tens to hundreds of billions of dollars per year.[2,3,73] For example, Figure 29.2 shows that reduced emissions under RCP4.5 can avoid approximately 48% (or $75 billion) of the $155 billion in lost wages per year by 2090 due to the effects of extreme temperature on labor (for example, outdoor industries reducing total labor hours during heat waves). Looking at the economy as a whole, mitigation can substantially reduce damages while also narrowing the uncertainty in potential adverse impacts (Figure 29.3).

Many impacts have significant societal or cultural values, such as impacts to freshwater recreational fishing. However, estimating the full value of these changes remains a challenge. Recent studies highlight that climate change can disproportionately affect socially vulnerable communities, with mitigation providing substantial risk reduction for these populations.[3,74,75,76] Some analyses also suggest that findings are sensitive to assumptions regarding adaptive capacity and socioeconomic change.[5,71,77] In general, studies find that reduced damages due to mitigation also reduce the potential level of adaptation needed.[2,78] As for socioeconomic change, increasing population growth can compound the damages occurring from climate change.[4,79] Some studies have shown that impacts can be more sensitive to demographic and economic conditions than to the differences in future climates between the scenarios.[80] See the Scenario Products section of Appendix 3 for more detail on population and land-use scenarios developed for the Fourth National Climate Assessment (NCA4).

For other sectors, such as impacts to coastal development, the effect of mitigation emerges more toward the end of the century due to lags in the response of ice sheets and oceans to warming (Ch. 8: Coastal).[81] This results in smaller relative reductions in risk. For example, while annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of

Estimates of Direct Economic Damage from Temperature Change

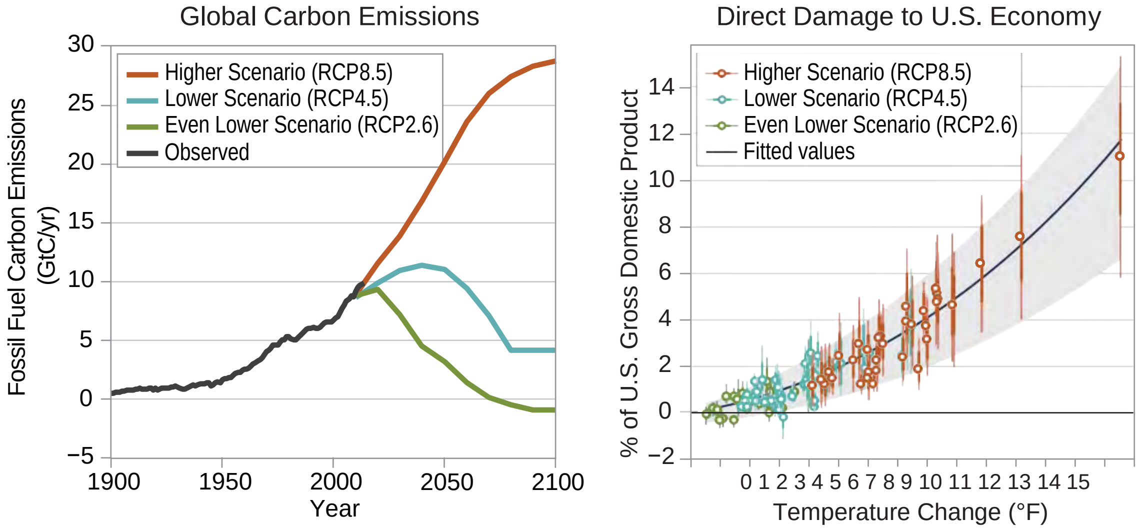

Figure 29.3: The left graph shows the observed and projected changes in fossil fuel and industrial emissions of CO_2 from human activities (emissions from land-use change do not appear in the figure; within the RCPs these emissions are less than 1 GtC per year by 2020 and fall thereafter). The right graph shows projections of direct damage to the current U.S. economy for six impact sectors (agriculture, crime, coasts, energy, heat mortality, and labor) as a function of global average temperature change (represented as average for 2080–2099 compared to 1980–2010). Compared to RCP8.5, lower temperatures due to mitigation under either of the lower scenarios (RCP2.6 or RCP4.5) substantially reduce median damages (dots) to the U.S. economy while also narrowing the uncertainty in potential adverse impacts. Dot-whiskers indicate the uncertainty in direct damages in 2090 (average of 2080–2099) derived from multiple combinations of climate models and forcing scenarios (dot, median; thick line, inner 66% credible interval; thin line, inner 90%). The gray shaded area represents the 90% confidence interval in the fit (black line) to the damage estimates. Damage estimates only capture adaptation to the extent that populations employed them in the historical period. Sources: (left) adapted from Wuebbles et al. 2017; [83] (right) adapted from Hsiang et al. 2017[3] and republished with permission of American Association for the Advancement of Science.

the century under RCP8.5, mitigation under RCP4.5 is projected to avoid less than a quarter of these damages.[2,5,82] However, the avoided impacts beyond 2100 are likely to be larger based on projected trajectories of sea level change.[19,20,27]

The marginal benefit, equivalently the avoided damages, of mitigation can be expressed as the social cost of carbon (SCC). The SCC is a monetized estimate of the long-term climate damages to society from an additional amount of CO_2 emitted and includes impacts that accrue in market sectors such as agriculture, energy services, and coastal resources, as well as nonmarket impacts on human health and ecosystems.[84,85] This metric is used to inform climate risk management decisions at national, state, and corporate levels.[86,87,88,89,90] Notably, estimating the SCC depends on normative social values such as time preference, risk aversion, and equity considerations that can lead to a range of values. In recognition of the ongoing examination about existing approaches to estimating the SCC,[91,92,93] a National Academies of Sciences, Engineering, and Medicine report[94] recommended various improvements to SCC models, including that they 1) be consistent with the current state of scientific knowledge, 2) characterize and quantify key uncertainties, and 3) be clearly documented and reproducible.

Although uncertainties still remain, advancements in climate impacts and economics modeling are increasingly providing new capabilities to quantify future societal effects of climate change. A growing body of studies use and assess statistical relationships between observed socioeconomic outcomes and weather or climate variables to estimate the impacts of climate change (e.g., Müller et al. 2017, Hsiang et al. 2017 [3,95]). In the United States, in particular, the rise of big data (large volumes of data brought about via the digital age) and advanced computational power offer potential improvements to study climate impacts in many sectors like agriculture, energy, and health, including previously omitted sectors such as crime, conflict, political turnover, and labor productivity. Parallel advancements in high-resolution integrated assessment models (those that jointly simulate changes in physical and socioeconomic systems), as well as process-based sectoral models (those with detailed representations of changes in a single sector), enable impact projections with increased regional specificity, which across the modeling frameworks shown in Table 29.1 reveal complex spatial patterns of impacts for many sectors. For example, this spatial variability is consistently observed in the agriculture sector,[2,5,96,97] where the large number of domestic crops and growing regions respond to changes in climate and atmospheric CO_2 concentrations in differing ways. As such, the benefits of mitigation for agriculture can vary substantially across regions of the United States and summing regional results into national estimates can obscure important effects at the local level.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences. Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors. This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable.

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population (Ch. 28: Adaptation). For example, recent studies have found that adaptation can substantially reduce climate damages in a number of sectors in both the higher (RCP8.5) and lower (RCP4.5) scenarios.[2,5] Damages to infrastructure, such as road and rail networks, are particularly sensitive to adaptation assumptions, with proactive measures (such as planned maintenance and repairs that account for future climate risks) estimated to be able to reduce damages by large fractions. More than half of damages to coastal property are estimated to be avoidable through well-timed adaptation measures, such as shoreline protection and beach replenishment.[2,5,196] In the health sector, accounting for possible physiological adaptation (acclimatization) to higher temperatures and for increased air conditioning use reduced estimated mortality by half,[2,5] a finding supported by other analyses of mortality from extreme heat.[99,100] However, adaptation can require large up-front costs and long-term commitments for maintenance (Ch. 28: Adaptation), and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk.[101]

Broadly, quantifying the potential effect of adaptation on impacts remains a research challenge (see the “Direction for Future Research” section) (see also Ch. 17: Complex Systems).[102] Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and adaptation activities can be considered complementary strategies.[196,103,104,105]

Adaptation and mitigation strategies can also interact, with the potential for benefits and/or adverse consequences.[106] An iterative risk-management approach for assessing and modifying these strategies as experience is gained can be advantageous (Ch. 28: Adaptation). Benefits occur when mitigation strategies make adaptation easier (or vice versa). For example, by reducing climate change and its subsequent effects on the water cycle, mitigation has been projected to reduce water shortages in most river basins of the United States, making adaptation to hydrologic impacts more manageable.[107] Also, carbon sequestration through reforestation and/or other protective measures can promote forest ecosystem services (including reduced flood risk), provide habitat for otherwise vulnerable species, or abate urban heat islands. Carbon sequestration measures in agriculture can reduce erosion and runoff, reducing vulnerability to extreme precipitation. Agricultural adaptation strategies that increase yields (such as altering crop varieties, irrigation practices, and fertilizer application), particularly in already high-yielding regions including North America, can have mitigation benefits (Ch. 10: Ag & Rural).[108] First, higher productivity lessens the need for clearing new land for production, thereby reducing associated emissions.[109] Second, these strategies counteract yield losses due to climate change,[2,110,111] which could enhance the ability to produce bioenergy crops or make additional land available for carbon sequestration.

In buildings and industrial facilities, adaptation measures such as investments in energy efficiency (for example, through efficient building materials) would reduce building energy demand (and therefore emissions), as well as lessen the impacts of extreme heat events.[112,113]

Adaptation and mitigation can also interact negatively. For example, if mitigation strategies include large-scale use of bioenergy crops to produce low-carbon energy, higher irrigation demand can lead to an increase in water stress that more than offsets the benefits of lessened climate change.[114] Similarly, mitigation approaches such as afforestation (the establishment of a forest where no previous tree cover existed) and concentrated solar power would increase demand for water and land.[115] Likewise, some adaptation measures such as irrigation, desalination, and air conditioning are energy intensive and would lead to increased emissions or create greater demands for clean energy. Higher air conditioning demands are projected to increase annual average and peak demands for electricity, putting added stress on an electrical grid that is already vulnerable to the effects of climate change (Ch. 4: Energy, KM 1).[2,116,117] Meeting these higher demands becomes more challenging as higher temperatures reduce the peak capacity of thermal generation technologies and lower peak transmission capacity.[118] In addition, complications are expected to arise when climate change impacts occur simultaneously and undermine adaptation measures, such as when a severe storm disrupts power over an extended time of intense heat, which can nullify the benefits of air conditioning adaptation.

Box 29.2: Co-Effects of Mitigation Actions

Recent scientific studies suggest that considering the indirect effects of mitigation can significantly reduce or eliminate the potential costs associated with cutting GHG emissions. This is due to the presence of co-benefits, often immediate, associated with emissions reductions, such as improving air quality and public health. There is now a large body of scientific literature evaluating 1) the health co-benefits of mitigation actions,[5,119,120,121,122,123,124,125] 2) improvement to crop yields,[126,127] and 3) a reduction in the probability of occurrence of extreme weather and climate-related events over the next decades that would otherwise occur with unabated emissions.[29] In transportation, for example, switching away from petroleum to potentially lower GHG fuels, such as electricity and hydrogen, is projected to reduce local air pollution. In California, drastic GHG emissions reductions have been estimated to substantially improve air quality and reduce local particulate matter emissions associated with freight transport that disproportionately impact disadvantaged communities.[128,129] Decarbonization of the energy system is also expected to increase energy security by increasing reliance on sources of energy that are produced domestically.[130,131]

At the same time, mitigation actions can have potential adverse effects, such as impacts to the cost of food and biodiversity loss due to the increased use of energy from biomass.[132,133] For this reason, it is more appropriate to use the term co-effects to refer to both benefits and costs associated with efforts to reduce GHG emissions.[123] The co-effects of investments in GHG emissions reductions generally occur in the near term, whereas the benefits of reducing GHG emissions will likely be mostly realized over longer timescales.

Box 29.3: Reducing Risk Through Climate Intervention

Climate intervention techniques (or geoengineering) are aimed at limiting global or regional temperature increase by affecting net radiative forcing through means other than emissions reductions (for a more detailed discussion see DeAngelo et al. 2017[9]). There are two broad categories of climate intervention techniques. One is carbon dioxide removal (CDR), which would reduce atmospheric CO_2 concentrations by changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO_2 through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO_2.[16] The second is solar radiation management (SRM), which would increase Earth's regional and/or global reflectivity by, for example, injecting sulfur gases or other substances into the stratosphere or brightening marine clouds. CDR is estimated to have long implementation times, and while costs (and their uncertainties) range widely across different measures,[134] it is estimated to be expensive at scale.[10] Nonetheless, large-scale CDR can be competitive with more traditional GHG mitigation options when substantial mitigation is required, and therefore it is an element of many scenarios that feature deep emissions reductions or negative emissions. Its climate benefits are likely to be similar to those from emissions reductions since both strategies act through reduced atmospheric concentrations of GHGs. Studies point to the risks of reaching the limits of available land, water, or biogeochemical requirements of biomass-based approaches at scale sufficient to offset large emissions.[13,16,99,135,136] In contrast to CDR, SRM strategies are estimated to be relatively inexpensive and realize climate benefits within a few years. They could be targeted at regional as well as global temperature modification[137] and could be combined with mitigation to limit the rate or the peak magnitude of warming. However, SRM effects on other outcomes, including precipitation patterns, light availability, and atmospheric circulation, are less well understood. In addition, SRM would not reduce risks from increasing atmospheric CO_2 concentra-

Box 29.3: Reducing Risk Through Climate Intervention, *continued*

tions such as ocean acidification.[138,139] Moreover, a sudden cessation of large-scale SRM activities could lead to very rapid climate changes, although a gradual phaseout of SRM as emissions reductions and CDR are phased in could avoid these abrupt changes. As concluded in Chapter 14 of the *Climate Science Special Report*, "Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as-yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence."[9]

Direction for Future Research

Coordinated Impacts Modeling Analyses

Multisector impacts modeling frameworks can systematically address specific mitigation and adaptation research needs of the users of the National Climate Assessment. Improved coordination amongst multidisciplinary impact modeling teams could be very effective in informing future climate assessments.

The recent multisector impacts modeling frameworks described above have demonstrated several key advantages for producing policy-relevant information regarding the potential for mitigation to reduce climate change impacts. First, the use of internally consistent scenarios and assumptions in quantifying a broad range of impacts produces comparable estimates across sectors, regions, and time. Second, these frameworks can simulate specific mitigation and adaptation scenarios to investigate the multisector effectiveness of these actions in reducing risk over time. Third, these frameworks can be designed to systematically account for key dimensions of uncertainty along the causal chain—a difficult task when assessing uncoordinated studies from the literature, each with its own choices of scenarios and assumptions.

Advancements to Address Research Needs from the Third National Climate Assessment

While not an exact analog to this chapter, the Third National Climate Assessment (NCA3)[140] included a Research Needs chapter as part of the Response Strategies section that recommended five research goals: 1) improve understanding of the climate system and its drivers, 2) improve understanding of climate impacts and vulnerability, 3) increase understanding of adaptation pathways, 4) identify the mitigation options that reduce the risk of longer-term climate change, and 5) improve decision support and integrated assessment.[141] Several of these topics have seen substantial advancements since publication of NCA3, informing our understanding of avoided climate risks. For example, research findings related to climate system drivers and the characterization of uncertainty have helped to differentiate the physical and economic outcomes along alternative mitigation pathways.[3,20,30] Enormous growth in impacts, adaptation, and vulnerability (IAV) research has enabled more robust quantification of the relative impacts (avoided damages) corresponding to different climate outcomes. However, challenges remain in accounting for the reduced risks and impacts associated with nonlinearities in the climate system, including tipping points such as destabilization of the West Antarctic ice sheet or rapid methane release from thawing permafrost.[22,98,142,143] Mitigation options continue to be studied to better understand their potential role in meeting different climate targets, and while many low-emitting or renewable technologies have seen rapid penetration, other strategies involving negative-emissions technologies have prompted caution due to the challenges of achieving widespread deployment at low cost. Adaptation pathways are better understood but continue to be a source of uncertainty related to understanding climate risk and local adaptation decision-making processes. Decision support for climate risk management, especially under uncertainty, is an area of active research,[144,145] and despite the limitations of integrated assessment models,[146,147] they offer useful insights for decision-makers.[148]

Remaining Knowledge Gaps

Despite ongoing progress, this assessment finds that significant knowledge gaps remain in many of the research goals and foundational crosscutting capabilities identified in NCA3. Going forward, it will be critically important to reduce uncertainties under different mitigation scenarios in 1) avoided sectoral impacts, such as agriculture and health, and 2) the capacity for adaptation to reduce impacts. Gaps in information on social vulnerability and exposure continue to hamper progress on disaster risk reduction associated with climate impacts.[51] Directions for future research in the climate science and impacts field include improved understanding of the avoided/increased risk of thresholds, tipping points, or irreversible outcomes (see Kopp et al. 2017[22]). Specific examples deserving further study include marine ice sheet instability and transformation of specific terrestrial carbon sinks into sources of greenhouse gas emissions.[149,150]

Gaps remain in quantifying combined impacts and natural feedbacks. For example, coral reef health includes combined stress/relief from changes in local activities (for example, agricultural and other nutrient runoff and fishery management), ocean acidification, ocean temperature, and the ability of coral species to adapt to changing conditions or repeated extreme events.[151,152] Additional knowledge gaps include an understanding of how mitigation and adaptation actions affect climate outcomes due to interactions in the coupled human–earth system.[142,153]

Interdisciplinary collaboration can play a critical role in addressing these knowledge gaps (such as coordinating a research plan across physical, natural, and social sciences).[52,154] Combining advances in scientific understanding of the climate system with scenarios to explore socioeconomic responses is expected to lead to an improved understanding of the coupled human–earth system that can better support effective adaptation and mitigation responses. Barriers to implementation arise from data limits (for example, the need for long-term observational records), as well as computational limits that increase model uncertainties.[53]

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Traceable Accounts

Process Description

The scope for this chapter was determined by the federal Fourth National Climate Assessment (NCA4) Steering Committee, which is made up of representatives from the U.S. Global Change Research Program (USGCRP) member agencies (see App. 1: Process for more information regarding the Steering Committee). The scope was also informed by research needs identified in the Third National Climate Assessment (NCA3) and in subsequent gap analyses.[155] Prospective authors were nominated by their respective agency, university, organization, or peers. All prospective authors were interviewed with respect to their qualifications and expertise. Authors were selected to represent the diverse perspectives relevant to mitigation, with the final team providing perspectives from federal and state agencies, nonfederal climate research organizations, and the private sector. The author team sought public input on the chapter scope and outline through a webinar and during presentations at conferences and workshops.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors during extensive teleconferences, workshops, and email exchanges. These discussions were informed by the results of a comprehensive literature review, including the research focused on estimating the avoided or reduced risks of climate change. The authors considered inputs submitted by the public, stakeholders, and federal agencies and improved the chapter based on rounds of review by the public, National Academies of Sciences, Engineering, and Medicine, and federal agencies. The author team also engaged in targeted consultations during multiple exchanges with contributing authors from other chapters of this assessment, as well as authors of the *Climate Science Special Report* (CSSR). For additional information on the overall report process, see Appendix 1: Process.

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector (*very high confidence*). Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions (*very high confidence*).

Description of evidence base

Since NCA3, state, local, and tribal entities have announced new or enhanced efforts to reduce greenhouse gas (GHG) emissions. While some policies with emissions co-benefits have been eliminated, on net there has been an increase in initiatives aimed at reducing emissions. Figure 29.1 includes several types of state-level efforts and is sourced from Figure ES-3 of the America's Pledge Phase 1 report, the most comprehensive listing of efforts across sectors currently available. The underlying state information is sourced from the U.S. Department of Energy, Appliance Standards Awareness Project, Open Energy Information, Rethink Food Waste Through Economics and Data, World Resources Institute, State of New York, California Air Resources Board, University of Minnesota, Land Trust Alliance, and the U.S. Forest Service.

U.S. state and local carbon pricing programs have increased in number since NCA3.[156] The Regional Greenhouse Gas Initiative has expanded the depth of emissions reductions activities and is considering adding transportation to their scope. California's cap and trade program started in 2012 and expanded by linking to Quebec and Ontario in 2017. Emissions trading systems are scheduled in Massachusetts and under consideration in Virginia.[156]

U.S. states have both mandatory and voluntary programs that vary in stringency and impact. For example, 29 states, Washington, DC, and 3 territories have Renewable Portfolio Standards (RPS; https://energy.gov/eere/slsc/renewable-portfolio-standards-resources), which require some portion of electricity to be sourced from renewable energy; while 8 states and 1 territory have voluntary renewable portfolio goals.[42,45] Likewise, 20 states have mandatory statewide Energy Efficiency Resource Standards (EERS; https://energy.gov/eere/slsc/energy-efficiency-resource-standards-resources), and 8 states have energy efficiency goals.[42] While the number of states with RPS and EERS policies remains similar to that during NCA3, emissions reductions associated with the impact of these policies have and are projected to increase.[157] In 2013, 8 states initiated an effort to coordinate implementation of their state zero-emission vehicle programs and have since taken a wide range of actions.[158]

Federal budget levels for activities that have reduced GHG have remained steady over recent years. There is uncertainty around the implementation of federal initiatives, in part owing to the implementation of Executive Order 13783.[40,159] Federal energy-related research and development have several co-benefits, including reduced emissions.[15]

U.S. companies that report through the Carbon Disclosure Project increasingly (although not comprehensively) reported board-level oversight on climate issues, which rose from 50% in 2011 to 71% in 2017. Likewise, 59 U.S. companies recently committed to set science-based emissions reduction targets.[46] U.S. businesses are increasingly pricing carbon.[46,160] Corporate procurement of utility-scale solar has grown by an order of magnitude since 2014.[47]

As indicated in the Education Institutions Reporting Database, a growing number of universities have made emissions reduction commitments or deepened existing commitments[161] as well as publicized the progress on their efforts.[162]

Major uncertainties

Figure 29.1 shows a count of each type of 30 measures across 6 categories, but it does not explore the relative stringency or emissions impact of the measures. The size, scope, time frame, and enforceability of the measures vary across states. Some state efforts and the majority of city efforts are voluntary, and therefore standards for reporting are heterogeneous. Efforts are underway to provide a rigorous accounting of the cumulative scale of these initiatives. Data collection through the America's Pledge effort is an ongoing, iterative process and, by necessity, involves aggregating different measures into categories. Historically, state, local, and corporate policies change on different cycles.

Description of confidence and likelihood

There is *very high confidence* that state, local, and private entities are increasingly taking, or are committed to taking, GHG mitigation action. Public statements and collated indices show an upward trend in the number of commitments, as well as the breadth and depth of commitments over the past five years.

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment (*very high confidence*). Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century (*high confidence*). It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent (*very high confidence*).

Description of evidence base

Recent scientific and economic advances are improving the ability to understand and quantify the physical and economic impacts of climate change in the United States, including how those risks can be avoided or reduced through large-scale GHG mitigation. While the projected impacts of climate change across sectors and regions are well documented throughout this assessment, several multisector modeling projects are enabling the comparison of effects through the use of consistent scenarios and assumptions.[2,3,4,5] A well-recognized conclusion from the literature produced by these projects is that climate change is projected to adversely affect the U.S. economy, human health, and the environment, each of which is further detailed below. These estimated damages increase over time, especially under a higher scenario (RCP8.5). For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).[2,3,4,5] In Figure 29.2, wildfire is the only sector showing positive effects, a result driven in this particular study by projected shifts to vegetation with longer fire return intervals.[2] However, it is important to note that the analysis underlying this result did not quantify the broader economic effects associated with these vegetative shifts, including ecosystem disruption and changes to ecosystem services. See Chapter 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity, which generally show increases in annual area burned over time. See Chapter 25: Southwest for a discussion on aridification toward the end of this century under high emissions.

There is robust and consistent evidence that climate change is projected to adversely affect many components of the U.S. economy. Increasing temperatures, sea level rise, and changes in extreme events are projected to affect the built environment, including roads, bridges, railways, and coastal development. For example, coastal high tide flooding is projected to significantly increase the hours of delay for vehicles.[163] Annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of the century under RCP8.5 (Ch. 8: Coastal).[2,5] Projected annual repair costs in order for roads, bridges, and railways to maintain levels of service in light of climate change range in the billions to tens of billions of dollars under RCP8.5.[2,164] Numerous studies suggest that regional economies can also be at risk, especially when they are tied to environmental resources or ecosystem services that are particularly vulnerable to climate change. For example, projected declines in coral reef-based recreation[152,165,166] would lead to decreases in tourism revenue; shorter seasons for winter recreation would likely lead to the closure of ski areas and resorts;[167,168,169,170] and increased risks of harmful algal blooms can limit reservoir recreation (Ch. 3: Water).[171,172]

An increasing body of literature indicates that impacts to human health are likely to have some of the largest effects on the economy. Studies consistently indicate that climate-driven changes to morbidity and mortality can be substantial.[72,100,173,174,175,176] In some sectors, the value of health damages is estimated to reach hundreds of billions of dollars per year under RCP8.5 by the end of the century. A large fraction of total health damages is due to mortality, quantified using the Value of a Statistical Life (VSL) approach based on standard VSL values used in federal government regulatory analysis.[177] For example, annual damages associated with extreme temperature-related deaths are estimated at $140 billion by the end of the century under RCP8.5, while lost wages from extreme temperatures, especially for outdoor industries, are projected at $160 billion per year by 2090.[2] Adaptive actions, including physiological adaptation and increased availability of air conditioning, are projected to reduce extreme temperature mortality by approximately half; however, the implementation costs of those adaptations were not estimated. Although less studied compared to the research on the direct effects of temperature on health, climate-driven impacts to air quality[72,178] and aeroallergens[173,179] are also projected to have large economic effects, due to increases in medical expenditures (such as emergency room visits) and premature mortality (Ch. 13: Air Quality).

Multiple lines of research have also shown that some climate change impacts will very likely be irreversible for thousands of years. For some species, the rate and magnitude of climate change projected for the 21st century is projected to increase the risk of extinction or extirpation (local-scale extinction) from the United States.[180,181,182,183] Coral reefs, coldwater fish, and high-elevation species are particularly vulnerable (Ch. 9: Oceans; Ch. 7: Ecosystems). The rapid and widespread climate changes occurring in the Arctic and Antarctic are leading to the loss of mountain glaciers and shrinking continental ice sheets.[69,184] The contribution of this land ice volume to the rate of global sea level rise is projected to affect U.S. coastlines for centuries (Ch. 8: Coastal).[19,30,185]

Major uncertainties

This Key Message reflects consideration of the findings of several recent multisector modeling projects (e.g., Hsiang et al. 2017, O’Neill et al. 2017, EPA 2017, Houser et al. 2015 [2,3,4,5]) released since NCA3. Despite these improvements to quantify the physical and economic impacts of climate change across sectors, uncertainty exists regarding the ultimate timing and magnitude of changes, particularly at local to regional scales. The sources of uncertainty vary by sector and the modeling approaches applied. Each approach also varies in its capacity to measure the ability of adaptation to reduce vulnerability, exposure, and risk. While the coverage of impacts has improved with recent advancements in the science, many important climate change effects remain unstudied, as do the interactions between sectors (Ch. 17: Complex Systems).[85] Finally, as climate conditions pass further outside the natural variability experienced over past several millennia, the odds of crossing thresholds or tipping points (such as the loss of Arctic summer sea ice) increase, though these thresholds are not well represented in current models.[22,142]

Description of confidence and likelihood

There is *very high confidence* that climate change is projected to substantially affect American livelihoods and well-being in the future compared to a future without climate change. The evidence supporting this conclusion is based on agreement across a large number of studies analyzing impacts across a multitude of sectors, scenarios, and regions. The literature clearly indicates that the adverse impacts of climate change are projected to substantially outweigh the positive effects. Although important uncertainties exist that affect our understanding of the timing and magnitude of some impacts, there is *very high confidence* that some effects will very likely lead to changes that are irreversible on human timescales.

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region (*very high confidence*). The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter (*very high confidence*).

Description of evidence base

There are multiple lines of research and literature available to characterize the effect of large-scale GHG mitigation in avoiding or reducing the long-term risks of climate change in the United States. Recent multisector impacts modeling projects, all of which feature consistent sets of scenarios and assumptions across analyses, provide improved capabilities to compare impacts across sectors and regions, including the effect of global GHG mitigation in avoiding or reducing risks.[2,3,4,5] The results of these coordinated modeling projects consistently show reductions in impacts across sectors due to large-scale mitigation. For most sectors, this effect of mitigation typically becomes clear by mid-century and increases substantially in magnitude thereafter.
In some sectors, mitigation can provide large benefits. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (on net, and absent additional risk reduction through adaptation) thousands to tens of thousands of deaths per year from extreme temperatures,[2,5] hundreds to thousands of deaths per year from poor air quality,[2,72] and the loss of hundreds of millions of labor hours.[2,3,5]

Beyond these multisector modeling projects, an extensive literature of sector-specific studies compares impacts in the United States under alternative scenarios. A careful review of these studies, especially those published since the Third National Climate Assessment, finds strong and consistent support for the conclusion that global GHG mitigation can avoid or reduce the long-term risks of climate change in the United States. For example, mitigation is projected to reduce the risk of adverse impacts associated with extreme weather events,[29,186] temperature-related health effects,[99,100,175] agricultural yields,[187,188,189] and wildfires.[73,190,191]

The finding that the magnitude and timing of avoided risks vary by sector and region, as well as due to changes in socioeconomics and adaptive capacity, is consistently supported by the broad literature base of multisector analyses (e.g., Hsiang et al. 2017, O’Neill et al. 2017, EPA 2017, Houser et al. 2015[2,3,4,5]) and focused sector studies (e.g., Melvin et al. 2016, Neumann et al. 2014[71,77]). Complex spatial patterns of avoided risks are commonly observed across sectors, including for human health effects (e.g., Fann et al. 2015, Sarofim et al. 2016 [100,178]), agriculture (e.g., Beach et al. 2015 [192]), and water resources (e.g., Chapra et al. 2017, Wobus et al. 2017, EPA 2013[167,171,193]).

The weight of evidence among studies in the literature indicates that the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,[2,4,5,9] as the human-forced response may not yet have emerged from the noise of natural climate variability.[6] In evaluating and quantifying multisector impacts across alternative scenarios, the literature generally shows that the effect of near-term mitigation in avoiding damages increases substantially in magnitude after 2050.[2,4,5] For example, mitigation under RCP4.5 is projected to reduce the number of premature deaths and lost labor hours from extreme temperatures by 24% and 21% (respectively) by 2050, and 58% and 48% by 2090.[2] For coastal impacts, where inertia in the climate system leads to smaller differences in rates of sea level rise across scenarios, the effects of near-term mitigation only become evident toward the end of the century (Ch. 8: Coastal).[2,5,19]

Major uncertainties

Quantifying the multisector impacts of climate change involves a number of analytic steps, each of which has its own potential sources of uncertainty. The timing and magnitude of projected future climate change are uncertain due to the ambiguity introduced by human choices, natural variability, and scientific uncertainty, which includes uncertainty in both scientific modeling and climate sensitivity. One of the most prominent sources involves the projection of climate change at a regional level, which can vary based on assumptions about climate sensitivity, natural variability, and the use of any one particular climate model. Advancements in the ability of climate models to resolve key aspects of atmospheric circulation, improved statistical and dynamic downscaling procedures, and the use of multiple ensemble members in impact analyses have all increased the robustness of potential climate changes that drive impact estimates described in the recent literature. However, key uncertainties and challenges remain, including the structural differences between sectoral impact models, the ability to simulate future impacts at fine spatial and temporal resolutions, and insufficient approaches to quantify the economic value of changes in nonmarket goods and services.[85] In addition, the literature on economic damages of climate change in the United States is incomplete in coverage, and additional research is needed to better reflect future socioeconomic change, including the ability of adaptation to reduce risk.

Description of confidence and likelihood

There is *very high confidence* that large-scale reductions in GHG emissions throughout the 21st century are projected to reduce the level of climate change projected to occur in the United States, along with the adverse impacts affecting human health and the environment. Across the literature, there are limited instances where mitigation, compared to a higher emissions scenario, does not provide a net beneficial outcome for the United States. While the content of this chapter is primarily focused on the 21st century, confidence in the ability of mitigation to avoid or reduce impacts improves when considering impacts beyond 2100.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences (*very high confidence*). Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors (*very high confidence*). This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable (*very high confidence*).

Description of evidence base

Global-scale reductions in GHG emissions are projected to reduce many of the risks posed by climate change. However, Americans are already experiencing, and will continue to experience, impacts that have already been committed to because of past and present emissions.[5,9] In addition, multisector modeling frameworks demonstrate that mitigation is unlikely to completely avoid the adverse impacts of climate change.[2,3,4,5,27] These factors will likely necessitate widespread adaptation to climate change (Ch. 28: Adaptation); an expanding literature consistently indicates potential for the reduction of long-term risks and economic damages of climate change.[2,4,5,194] However, it is important to note that adaptation can require large up-front costs and long-term commitments for maintenance (Ch. 28: Adaptation), and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk.[101]

Because of adaptation's ability to reduce risk in ways that mitigation cannot, and vice versa, the weight of the evidence shows that the two strategies can act as complements. Several recent studies jointly model the effects of mitigation and adaptation in reducing overall risk to the impacts of climate change in the United States, focusing on infrastructure (e.g., Larsen et al. 2017, Melvin et al. 2016, Neumann et al. 2014 [71,77,195]) and agriculture (e.g., Kaye and Quemada 2017, Challinor et al. 2014, Lobell et al. 2013 [108,109,111]). Exploration of this mitigation and adaptation nexus is also advancing in the health sector, with both mitigation and adaptation (such as behavioral changes or physiological acclimatization) being projected to reduce deaths from extreme temperatures[100] in both the higher and lower emissions scenarios that are the focus of this chapter. Similarly, energy efficiency investments are reducing GHG emissions and operating costs and improving resilience to future power interruptions from extreme weather events (Ch. 14: Human Health). While more studies exploring the joint effects of mitigation and adaptation are needed, recent literature finds that combined mitigation and adaptation actions can substantially reduce the risks posed by climate change in several sectors.[2,103,104] However, several studies highlight that mitigation and adaptation can also interact negatively. While these studies are more limited in the literature, sectors exhibiting potential negative co-effects from mitigation and adaptation include the bioenergy–water resource nexus[114] and changes in electricity demand and supply in response to increased use of air conditioning.[2,117]

Major uncertainties

It is well understood that adaptation will likely reduce climate risks and that adaptation and mitigation interact. However, there are uncertainties regarding the magnitude, timing, and regional/sectoral distribution of these effects. Developing a full understanding of the interaction between mitigation and adaptation, with detailed accounting of potential positive and negative co-effects, is an important research objective that is only beginning to be explored in the detail necessary to inform effective implementation of these policies. Quantifying the effectiveness of adaptation requires detailed analyses regarding the timing and magnitude of how climate is projected to affect people living in the United States and their natural and built environments. As such, the uncertainties described under Key Messages 1 and 2 are also relevant here. Further, uncertainty exists regarding the effectiveness of adaptation measures in improving resilience to climate impacts. For some sectors, such as coastal development, protection measures (for example, elevating structures) have been well studied and implemented to reduce risk. However, the effectiveness of adaptation in other sectors, such as the physiological response to more intense heat waves, is only beginning to be understood.

Description of confidence and likelihood

There is *very high confidence* that the dual strategies of mitigation and adaptation being taken at national, regional, and local levels provide complementary opportunities to reduce the risks posed by climate change. Studies consistently find that adaptation would be particularly important for impacts occurring over the next several decades, a time period in which the effects of large-scale mitigation would not yet be easily recognizable. However, further analysis is needed to help resolve uncertainties regarding the timing and magnitude of adaptation, including the potential positive and negative co-effects with mitigation.

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AI Appendix 1. Report Development Process

Assessments are essential tools for linking science and decision-making. The Global Change Research Act (GCRA) of 1990[1] charged the U.S. Global Change Research Program (USGCRP) with a legal mandate to conduct a scientific assessment on the effects of global change not less frequently than every four years; the third and most recent National Climate Assessment (NCA) was released in May 2014.[2]

NCA Goal and Vision

In fulfillment of this mandate and in support of its Strategic Plan,[3,4] USGCRP coordinated this Fourth National Climate Assessment (NCA4), which focuses on advancing our collective understanding of how climate change poses risks to things of value to society. Much of the NCA4 process builds on the Third National Climate Assessment (NCA3),[2] and thus much of this process description is derived from that of NCA3. However, several changes have been made in light of lessons learned through an external evaluation of NCA3 (see "What Has Happened Since the Last National Climate Assessment?" in Ch. 1: Overview).[6] Some of those changes are discussed in greater detail in this appendix.

The vision for the NCA is to continue advancing an inclusive, broad-based, and sustained process for assessing and communicating scientific knowledge of the impacts, risks, and vulnerabilities associated with a changing global climate and to support informed decision-making across the United States.

Legislative Foundations

U.S. Global Change Research Program

Founded by Presidential Initiative in 1989, the U.S. Global Change Research Program aims to build a knowledge base that informs human responses to climate and global change through coordinated and integrated federal programs of research, education, communication, and decision support.

The Global Change Research Act of 1990 cemented into law what was started by President Ronald Reagan. USGCRP is mandated to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict and respond to human-induced and natural processes of global change."[1]

National Climate Assessment

Section 106 of the GCRA requires a report to the President and the Congress not less frequently than every four years that 1) integrates, evaluates, and interprets the findings of the USGCRP; 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

Institutional Foundations

U.S. Global Change Research Program

USGCRP is a confederation of 13 federal departments and agencies (Figure A1.1) that supports the largest investment in climate and global change research in the world. USGCRP coordinates research activities across agencies, produces the congressionally mandated products, and provides data and products to inform decisions. USGCRP's Strategic Plan, released in 2012 and updated in 2017, focuses on four major goals: advance science, inform decisions, conduct sustained assessments, and communicate and educate.[3,4] The USGCRP agencies maintain and develop observations, monitoring assets, data management, analysis of data products, and modeling capabilities that support the Nation's response to global change. The agencies that make up USGCRP are:

Department of Agriculture (USDA)

Department of Commerce (DOC)

Department of Defense (DOD)

Department of Energy (DOE)

Department of Health and Human Services (HHS)

Department of the Interior (DOI)

Department of State (DOS)

Department of Transportation (DOT)

Environmental Protection Agency (EPA)

National Aeronautics and Space Administration (NASA)

National Science Foundation (NSF)

The Smithsonian Institution (SI)

U.S. Agency for International Development (USAID)

The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities. The SGCR operates under the direction of the National Science and Technology Council's Committee on the Environment (CoE) and is overseen by the White House Office of Science and Technology Policy (OSTP). The SGCR coordinates interagency activities through the USGCRP National Coordination Office (NCO) and informal interagency working groups (IWGs).

National Climate Assessment Components

The **NCA4 Federal Steering Committee (NCA4 SC)** consists of representatives of the USGCRP member agencies, listed above. In consultation with the SGCR, the NCA4 SC was responsible for the development, production, and content of NCA4 (Figures A1.2, A1.3). The NCA4 SC was charged with overseeing development of technical content and with conducting high-level scoping of the report to ensure coherence, relevance, and responsiveness to the Global Change Research Act and the USGCRP Strategic Plan. The NCA4 SC was also responsible for ensuring that the report development process was robust and that it adhered to the principles of engagement and transparency that are crucial to the process

Figure A1.1: Logos of the 13 agencies that make up USGCRP.

of conducting sustained assessments. In some ways, the NCA4 SC served in a similar capacity to the National Climate Assessment and Development Advisory Committee (NCADAC) during the course of NCA3 development. The NCA4 SC met weekly during the early stages of the report's development before moving towards a more quasi-monthly meeting schedule once writing began in earnest.

The **Administrative Agency** of NCA4 was the National Oceanic and Atmospheric Administration (NOAA). In this role, NOAA was responsible for providing oversight and access to federal resources for the NCA, including (but not limited to) leadership on the NCA4 SC, management of Federal Register Notices, and dedicated funding of external engagement activities, among other supportive activities.

Agency Chapter Leads (ACLs) oversaw the production of national-level topic or response chapters and were in charge administratively of their chapter's development.

Federal Coordinating Lead Authors (CLAs) were selected for each chapter—some chapters had two—by the NCA4 SC, in consultation with the SGCR. A key role of the CLAs was to serve as "horizontal integrators" for NCA4—working with one another to ensure that crosscutting issues were addressed consistently, accurately, and adequately. They also ensured that the chapter draft ultimately delivered to them adhered to their Agency's criteria for a Highly Influential Scientific Assessment.

Chapter Leads (CLs; both federal and non-federal) served as "vertical integrators" for NCA4, selecting and directing their respective author team and then providing a draft of their chapter to the CLA(s). National Chapter Leads (NCLs), for the topic and response chapters, were selected by the ACL for the chapter, while the Regional Chapter Leads (RCLs) were selected from experts nominated during a public open call by the NCA4 SC.

Chapter Authors (CAs) constituted the bulk of the chapter author team and were the main authors of the individual chapters. The CLs directed the CAs to contribute to the writing and editing of the chapters. The CLs chose the CAs based on the specific needs of the chapter. CLs were provided guidance to convene a diverse group of experts along with the full slate of nominees received during the public call for authors.

Review Editors (REs) were selected by the NCA4 SC after a public call for nominees. They were responsible for ensuring that all substantive comments—submitted during the Public Comment Period and via a National Academies of Sciences, Engineering, and Medicine (NASEM) expert review panel—were appropriately addressed and documented. REs advised CLs on how to handle contentious issues and to ensure that significant scientific uncertainties were reflected adequately in the text of NCA4.

Technical Contributors (TCs) were invited to contribute to the chapter author team for discrete, specific issues on an as-needed basis, as identified by the CL.

The USGCRP **National Coordination Office (NCO)** in Washington, DC, provided support for the development of NCA4 through a team of contracted staff and federal detailees with expertise in planning, writing, and coordinating collaborative climate and environmental science activities. NCO staff provided monthly updates on NCA4 progress and activities to the SGCR Principals, while also—beginning in February 2017—posting similar content at http://www.globalchange.gov/news so the public could track progress.

The **NCA Technical Support Unit (TSU)** is funded by NOAA and is located at NOAA's National Centers for Environmental Information in Asheville, North Carolina; its professional staff supports the Assessment's climate science findings, data management and web design, graphics and publications, editing, and other production activities.

NCA4 Authorship Models

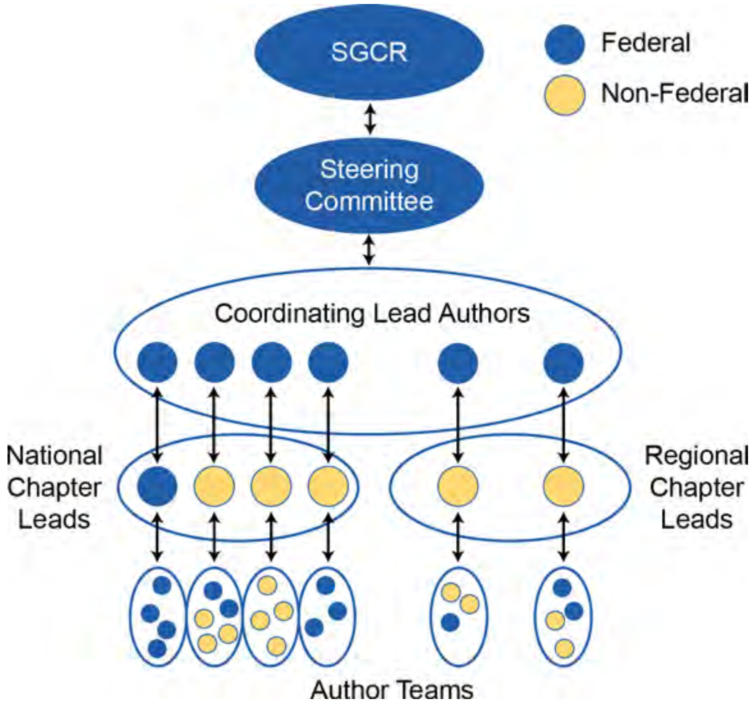

Figure A1.2: In consultation with the Subcommittee on Global Change Research (SGCR), the NCA4 Federal Steering Committee (NCA4 SC) selected Coordinating Lead Authors (CLAs) for each chapter of the NCA. CLAs worked one-on-one with either National or Regional Chapter Leads (CLs), who in turn directed Chapter Authors (CAs). A mix of authorship models including both federal and nonfederal participants was used for NCA4. Source: USGCRP.

Organization of the National Climate Assessment Participants

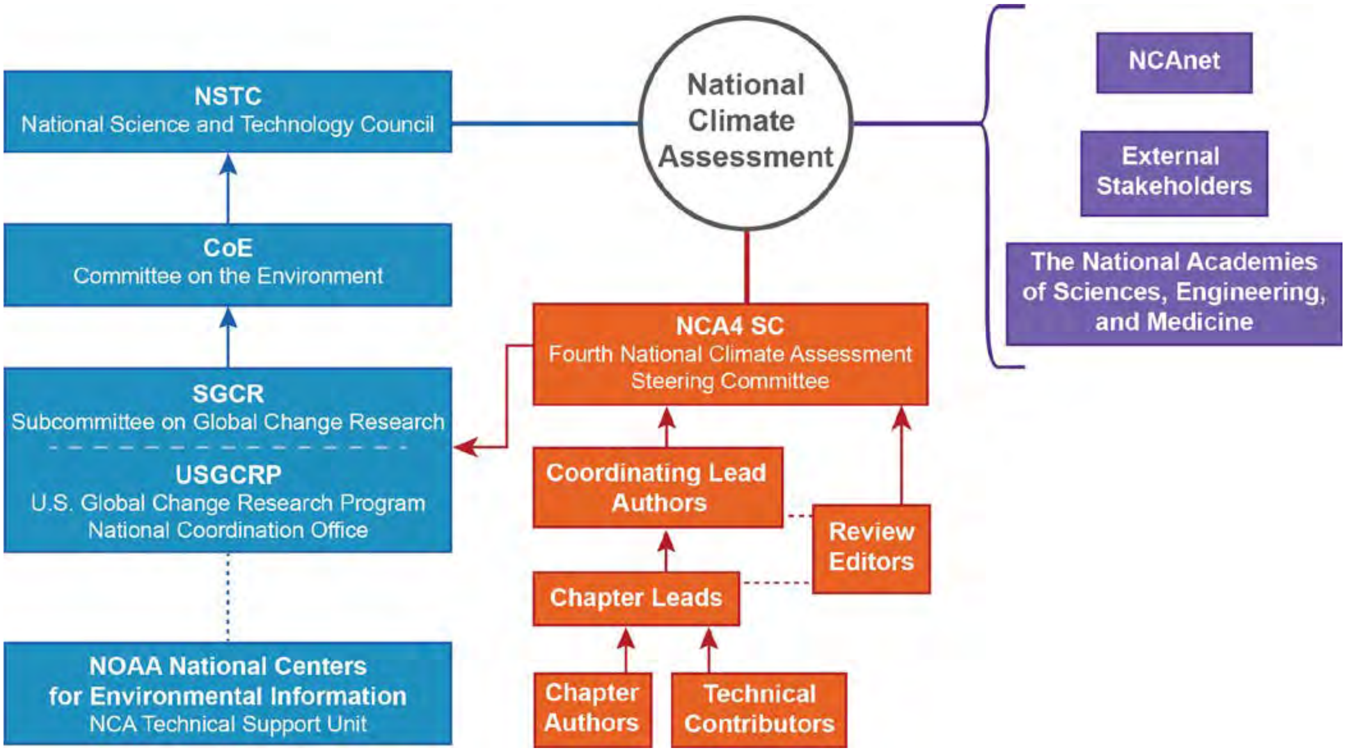

Figure A1.3: Participants in the NCA process can be divided into three broad categories: 1) federal agencies and offices, including the USGCRP (blue boxes); 2) external partners and relevant stakeholders (purple boxes); and 3) NCA4 contributors, including the Federal Steering Committee and report authors (orange boxes). Source: USGCRP.

The **National Climate Assessment Network (NCAnet)** consists of more than 200 organizations that work with the NCO, report authors, and USGCRP agencies to engage producers and users of assessment information.[7] Partners extend and amplify the NCA process and products to a broad audience through the development of assessment-related capacities and products, such as collecting and synthesizing data or other technical and scientific information relevant to the NCA, disseminating NCA report findings to a wide range of users, engaging producers and users of assessment information, supporting NCA events, and producing communications materials related to the NCA and NCA report findings.

Creating the Fourth NCA Report

Process Development

In May 2015, a Federal Register Notice[8] requested information to help inform the structure and content of USGCRP's sustained National Climate Assessment process, which NCA4 is a part of. In early 2016, the SGCR Principals designated the NCA4 SC to lead NCA4 development, and the NCA4 SC began its work, building on prior work from the Interagency National Climate Assessment (INCA) Working Group, the NCADAC, experiences of TSU and NCO staff, and feedback from the aforementioned public call for information (Figure A1.4).

In July 2016, a Federal Register Notice[9] was published, seeking input on the draft outline for NCA4. Subsequently, a Federal Register Notice[10] was published in late August 2016, serving as both a call for regional Chapter Leads and other authors (open call for 30 days) and a call for technical inputs (this part of the call was open for a longer time period, until mid-January 2017).

Concurrent with these public calls for nominations and technical inputs, the NCA4 SC, NCO staff, and TSU staff developed guidance documents for use during the development of NCA4, ranging from chapter and Traceable Accounts templates to style guides and a literature resource database. Risk-based framing was integrated into the chapter templates and other drafting guidance. Authors had access throughout the process to scientific resources and writing guidance materials on a password-protected Resources website, hosted by the TSU, that also served as a collaboration space for authors.

Report Process

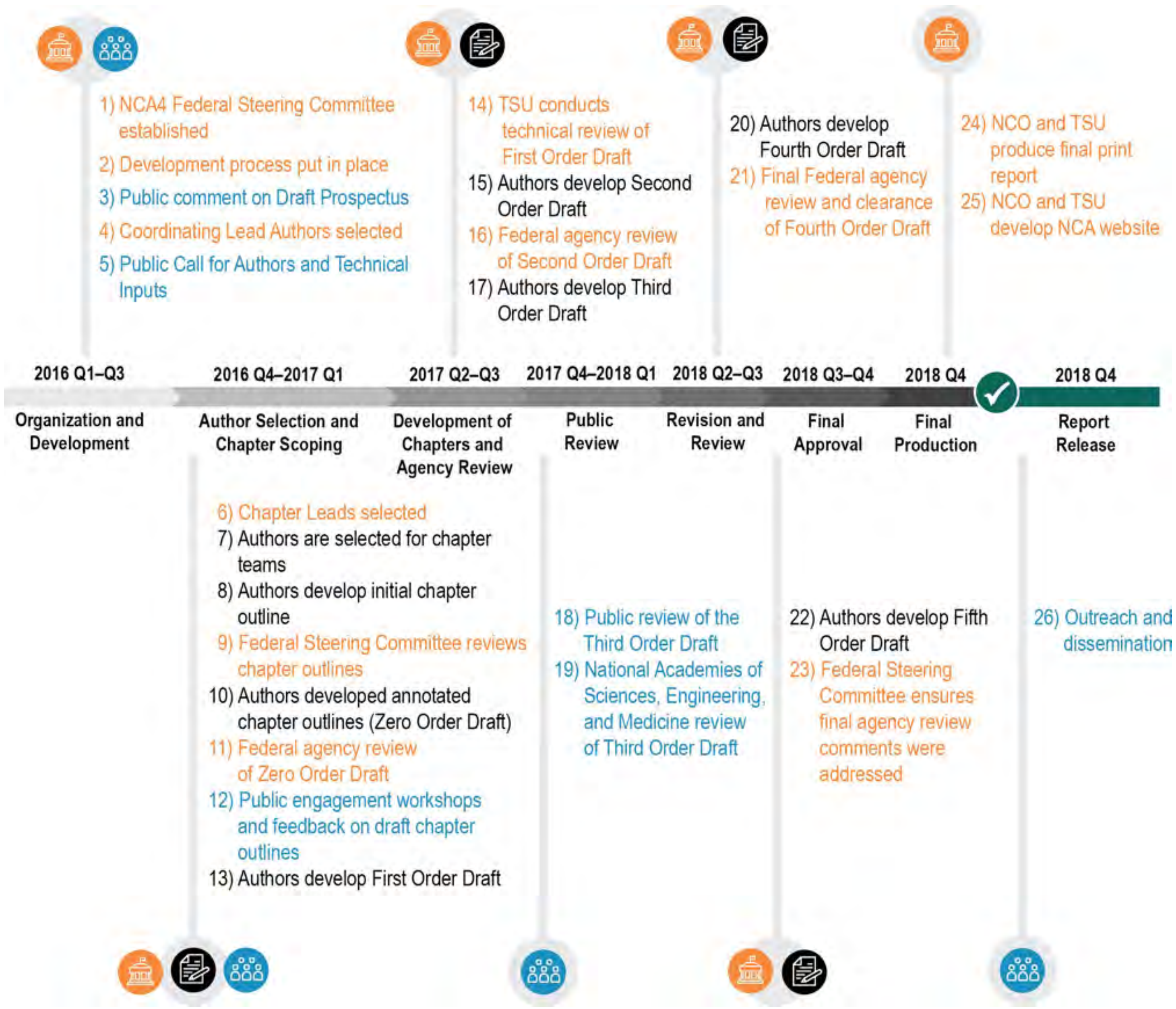

Figure A1.4: This is a graphic illustration of the NCA4 development process. Multiple points of federal review and decision (orange icons) were present throughout the process. In addition, public engagement (blue icons) was a cornerstone of the NCA development process. Authors used these feedback mechanisms to inform the development and execution of their chapters (black icons). Source: USGCRP.

Author Selection, Role, and Preliminary Work (Autumn 2016)

In the fall of 2016, the NCA4 SC selected one or two federal **Coordinating Lead Authors** (CLAs) for each chapter, based on criteria that included expertise and experience and that ensured a variety of perspectives. As the author teams were being assembled (described below), the CLAs and many of the CLs began scoping their chapters. In addition, in October 2016, a CLA meeting was held in Washington, DC, to provide context and guidance for the CLAs moving forward with the NCA4 process.

National Chapter Leads (NCLs), for the topic and response chapters, were selected by the Agency Chapter Lead for each national chapter. The NCA4 SC selected the **Regional Chapter Leads** (RCLs) from a pool of nominated authors derived from a call for nominations in the Federal Register Notice,[10] described above. These NCLs and RCLs, with input and guidance from the NCA4 SC, selected federal and nonfederal **Chapter Authors** (CAs) to establish chapter author teams. CAs were identified based not only on the expertise and experience they would bring to the chapter, but also a commitment to ensuring that a diverse range of perspectives would be reflected in the drafting process. In addition, **Technical Contributors** (TCs) were enlisted at the discretion of the CL to provide specific technical input to the chapter as needed. Each chapter had a primary and backup NCO **Point of Contact** (POC) who supported the chapter team, provided clarity on drafting guidance, facilitated conversations, and assisted the CLA in identifying crosscutting issues.

Initial Chapter Outlines (December 2016 – January 2017)

Authors developed initial chapter outlines in December 2016. The NCA4 SC provided comments on these, which resulted in more complete chapter outlines in January 2017. An interagency review led by the SGCR provided a higher-level review of these more detailed outlines to further inform the development of each chapter.

Regional Engagement Workshops, Author Meetings, and Other Chapter Engagement (Spring 2017)

During late winter and early spring 2017, a series of **Regional Engagement Workshops** (REW; Figure A1.5) and National Chapter Engagement Webinars provided stakeholders with the opportunity to learn about the NCA4 process and provide additional input to author teams as they worked to deliver a First Order Draft of their chapters in June 2017. The hub-and-satellite model (a central hub with various additional sites around the region joining virtually) employed for the REWs resulted in participation in 44 cities and towns across the United States, reaching thousands of stakeholders. Workshop summary reports were shared with all NCA4 author teams to provide a consistent foundation for all report authors. These summary reports are available online at http://www.globalchange.gov/content/nca4-engagement-activities.

In addition, NCA4 authors, staff, and NCAnet affiliates organized, spoke at, and participated in a number of sessions at professional society meetings, web-based seminars, community meetings, and other events designed to provide a two-way exchange of information between NCA users and contributors.

Regional Engagement Around NCA4

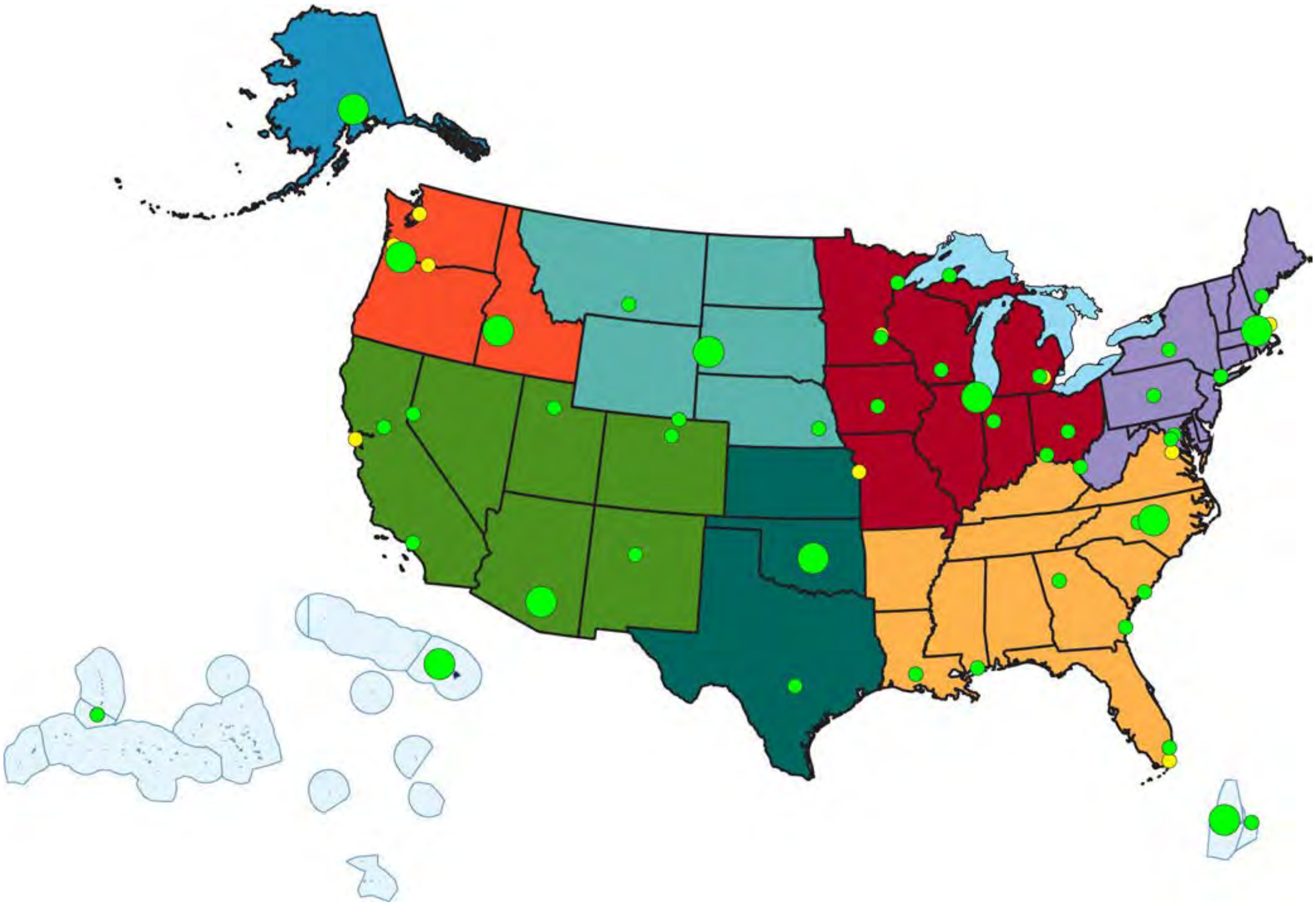

Figure A1.5: The large green dots illustrate the hub locations for the 11 Regional Engagement Workshops held across the country in February to March of 2017. The small green dots indicate satellite locations for those workshops, and the small yellow dots show the locations of some additional engagement activities, such as presentations or listening sessions at professional society meetings. Source: USGCRP.

Regional Engagement Workshops

Figure A1.6: Regional engagement workshops were held around the country in every NCA4 region to facilitate feedback from interested stakeholders on the outlines of the regional chapters. Workshops in San Juan, Puerto Rico, Norman, Oklahoma, Portland, Oregon, and Rapid City, South Dakota, are highlighted. Photo credits: (San Juan, PR photos) Gary Potts, USFS; (all others) USGCRP.

First Chapter Leadership Meeting (CLA-CL1)

On April 4–5, 2017, chapter leadership (CLAs and CLs) convened in Washington, DC, to work on cross-chapter coordination and to discuss additional guidance on chapter drafting, especially on Key Message and Traceable Account formulation. A particularly successful component of this two-day meeting was an extended “speed-dating” session, where CLAs and CLs from a given chapter would meet with their counterparts from another chapter for 30 minutes to discuss how crosscutting issues would be addressed in their respective chapters to ensure consistent, nonduplicative coverage of key issues.

First Chapter Leadership Meeting

Figure A1.7: Chapter leadership gathered in Washington, DC, for a two-day meeting intended to facilitate individual National Climate Assessment chapter development, inform leadership on process and logistical needs, and facilitate cross-chapter collaboration and information sharing. Photo credits: USGCRP.

Author Training and Drafting

Each of the author teams met multiple times by phone, web, and in person and produced multiple iterations of their chapters since beginning work in October 2016. Traceable Accounts developed for the chapters provide transparent information about the authors' deliberations to arrive at their expert judgment regarding the level of certainty related to the Key Messages of their chapter.

Monthly calls/webinars were generally held with all authors in order to provide them with updates and to address a variety of topics in an effort to ensure consistency across the report and to keep the Assessment progressing in a timely manner. In addition, USGCRP coordinated 14 author training webinars on the following topics:

- Available scenarios products and how to use them
- The EPA's Climate Change Impacts and Risk Analysis (CIRA) project[11]
- Lessons learned through previous assessments
- Key Message and Traceable Account development
- A walkthrough of the website for scenario products[12]
- Available regional- and local-scale climate variables, through the Localized Constructed Analogs (LOCA) system (see App. 3: Data & Scenarios for more information)
- Metadata requirements and the Global Change Information System (GCIS)
- Climate change indicators
- A report from the National Academies of Sciences, Engineering, and Medicine (NASEM) on *Characterizing Risk in Climate Assessments*[13]
- Risk-based framing
- *Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences* report[14]
- NCA4 Volume I: *Climate Science Special Report* (CSSR)
- NOAA's State Climate Summaries[16]
- External, expert peer-review of the draft report by an ad hoc panel of NASEM[17]

All author training webinars were recorded and archived on the password-protected Resources portal for authors to access at their convenience throughout the process.

Cross-Chapter Coordination

A key component of success in any broad assessment effort is a means of facilitating cross-chapter coordination. During NCA4, this was done throughout the drafting and review processes. The CLA-CL1 meeting facilitated high-level information sharing among chapter leadership, especially through the aforementioned speed-dating meetings between chapters. The Resources website also provided a forum for interim drafts to be posted and viewed by all author teams.

Specific author teams employed many other techniques. For example, the regional authors working on tribal and Indigenous topics began having regular phone meetings in the winter of 2017 and then began meeting with the authors of the national-level "Tribes and Indigenous Peoples" chapter to discuss consistent terminology and language framing around these topics. Authors of another national-scale chapter (Ch. 10: Ag & Rural) set up phone calls with authors from each of the regional chapters to ensure appropriate coverage of topical issues throughout the regions and to facilitate the roll-up of regional issues related to agriculture and rural communities to the higher-level synthesis chapter.

Review Editor Selection and Role

The NCA4 Federal Steering Committee selected Review Editors (REs) from a slate of candidates nominated through a public open call in the summer of 2017.[18] For their assigned chapter(s), REs ensured that all substantive comments submitted during the Public Comment Period and via an expert review panel of NASEM were appropriately addressed and documented. REs advised CLs on how to handle contentious issues and ensured that significant scientific uncertainties were reflected adequately in the text of NCA4. REs did not provide additional comments on assigned draft chapters but instead focused on the materials derived from the Public Comment Period and NASEM review. REs ensured that each and every comment had been considered by the author team and that the "annotation" (the written response to the comment) was responsive to the comment and indicated any revision made to the chapter(s), including the scientific or logical rationale for said action. REs helped the CLs ensure that the response to each review comment matched the final text of the revised, post-public/ NASEM review draft.

All-Author Meeting

On March 26–28, 2018, all chapter authors and review editors were invited to participate in a 2.5-day all-author workshop in Bethesda, Maryland. The workshop gave authors the opportunity to finalize cross-chapter references and finish edits in response to both public and NASEM reviews of the Third Order Draft.

Review Processes

To begin the writing process, author teams were instructed to develop high-level chapter outlines late in 2016 in light of comments received on the draft prospectus[9] and guidance provided to authors. The NCA4 Federal Steering Committee reviewed and provided comments on these high-level chapter outlines, which resulted in annotated outlines (Zero Order Drafts) provided to the SGCR for interagency review in January 2017. Comments from this interagency review, alongside input from the suite of public engagement events held throughout the spring of 2017, informed the development of a full First Order Draft.

With the receipt of the full First Order Draft in mid-June 2017, the TSU began an iterative technical editing process with the authors of each chapter to ensure that content was scientifically accurate, that topics were addressed consistently across chapters, and that the text and figures were accessible to the target audience. This process resulted in a Second Order Draft (SOD). A second round of interagency, SGCR-led review of this SOD occurred in the summer of 2017. Consequently, authors revised their chapters in response to these interagency comments, resulting in a Third Order Draft (TOD). This TOD was then released on November 3, 2017, for review by the public.[19] The three-month public review period allowed individuals and groups to examine the draft and provide comments to ensure that the report 1) presented the science accurately, 2) responded to user needs, and 3) relayed its findings in a clear and consistent manner. By the time the Public Comment Period closed on January 31, 2018, the online comment system had received 3,416 comments representing diverse perspectives from over 1,100 registrants (although a smaller number of individual registrants actually submitted comments). Concurrent to this public review period, NASEM convened an expert ad hoc committee to review the TOD and provided the authors with a formal, peer-reviewed external expert review.[17]

All-Author Meeting

Figure A1.8: Author teams gathered in Bethesda, Maryland, in March 2018 to finalize revisions in response to public and NASEM reviews (c, f) and to collaborate across chapters to ensure coherency across the report (a, d, e). More than 200 authors attended the meeting (b). Photo credits: USGCRP.

Chapter author teams amended the TOD in response to these public and NASEM comments; they were required to respond to each and every comment. Review Editors evaluated the adequacy of the responses to the comments on each chapter. The public comments and the chapter authors' responses to those comments are available online with the final report (https://nca2018.globalchange.gov/downloads/).

The Fourth Order Draft (4OD) that resulted from the revisions made in response to the public and NASEM comments was then circulated to the interagency again for final federal review and clearance in late April 2018. Any comments that were submitted by the early June 2018 deadline were addressed by the authors during the summer of 2018, resulting in a Fifth Order Draft. In late summer 2018, each Agency's Federal Steering Committee member reviewed this final draft of the report to ensure that any agency comments submitted by the June deadline were adequately addressed.

NCA Final Report

After a production and layout phase in the autumn of 2018, a final public version of the report was published as a downloadable PDF in December 2018; an accompanying website (nca2018.globalchange.gov) was unveiled at the same time. A number of derivative products, including a "Report-in-Brief" document, were produced in addition to the full report.

Resources Available for Authors

The **Resources website** served as the primary compendium of guidance documents, recordings of training webinars, drafts in progress, and many other resources for authors. In addition, the Resources site contained forms to submit figure requests and the associated, required metadata.

Technical Inputs

A public call for technical inputs[10] resulted in the submission of more than 400 peer-reviewed journal articles, reports, and other contributions authored by hundreds of individuals from academia, industry, various levels of government, and nongovernmental organizations. Alongside this public set of technical inputs, the USGCRP NCO conducted a survey of high-impact scientific journals and other peer-reviewed sources to develop a searchable-by-chapter database of over 1,200 articles and reports for NCA4 authors to consider in their assessment.

In addition, the TSU climate science team developed 51 state climate summaries (one for each state, with a 51st summary on Puerto Rico and the U.S. Virgin Islands) to meet a demand for state-level information in the wake of NCA3.[16] The summaries cover assessment topics directly related to NOAA's mission, specifically historical climate variations and trends, future climate model projections of climate conditions during the 21st century, and past and future conditions of sea level and coastal flooding. Furthermore, EPA produced 50 state climate summaries plus one each for Guam, Puerto Rico, and the U.S. Virgin Islands, looking at historical climate impacts.[20]

The *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment* (CIRA2.0) was produced as a technical input to NCA4 and informs many chapters.[11] This report estimates the physical and monetary benefits to the United States of reducing global greenhouse gas emissions in 2050 and 2090 for more than 20 sectors of the American economy. Other technical reports produced since NCA3 and used as technical inputs to NCA4 include the U.S. Forest Service's *Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis*[21] and *Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences*.[14]

Special Assessment Reports

A number of federally produced scientific assessment reports provide a robust foundation from which NCA4 authors drew. An illustrative list of such USGCRP-sustained assessment products include:

The *Climate Science Special Report* (CSSR),[15] released in November 2017, is Volume I of NCA4. It provides the scientific underpinnings for NCA4 and serves as an update of the physical science as presented in NCA3.[2] Topics include detection and attribution; precipitation change; droughts, floods, and wildfire; extreme storms; sea level rise; ocean acidification; mitigation; potential surprises; and more.

The *Second State of the Carbon Cycle* (SOCCR2)[22] was released in December 2018 and provides an update on carbon cycle science across North America that informs several NCA4 chapters.

The *Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (referred to as the "Climate and Health Assessment") was released in April 2016 and strengthens our understanding of the linkages between climate change and health. It serves as an important input to NCA4,[23] covering such issues as temperature-related death and illness; air quality impacts; extreme events; vector-borne diseases; waterborne illness; food safety, nutrition, and distribution; mental health and well-being; and populations of concern.

The *Climate Change, Global Food Security, and the U.S. Food System* assessment was released in December 2015 and identifies climate change impacts on global food security. It provides input to many chapters,[24] covering such issues as non-climate drivers of food systems and security; models, scenarios, and projections of socioeconomic change; integrated assessment models of agricultural and food systems; food availability and stability; food access and stability; food utilization and stability; and global food security and the United States.

The *Third National Climate Assessment* (NCA3) was released in 2014 and covered many of the same sectors and geographical regions of the United States, providing a foundation for the sectors and regions in NCA4.[2] NCA4 includes several new national topic chapters and regions as a result of feedback from the public for such information.

Engagement Activities

The NCA Engagement Strategy,[25] developed for NCA3 and expanded for NCA4, provides a vision for participation, outreach, communications, and education processes that help make the NCA process and products more accessible and useful to many audiences. The overall goal of engagement is to create a more effective and successful NCA that is informed by and responsive to user needs—improving the processes and products of the effort so that they are credible and salient and build the capacity of participants to engage in the creation and use of these processes and products for decision-making.[25] The strategy describes a number of mechanisms through which scientific and technical experts, decision-makers, and members of the general public might learn about and participate in the NCA process.

The NCO organized listening sessions, symposia, webinars, and other sessions at professional society meetings to provide updates on the NCA process, solicit broad input from subject matter experts, and collect feedback on the approach, topics, and methodologies under consideration.

A series of **Regional Informational Webinars** were conducted in September 2016 to solicit technical inputs and nominations for authors and to discuss the NCA4 process. These included webinars targeted at each of the NCA4 regions (with the Southeast and U.S. Caribbean being combined), as well as one webinar focused on tribal and Indigenous communities and a final, national-level webinar intended for a general audience.

In addition, a series of **Public Comment Period Webinars** were offered from November 2017 through January 2018 to raise awareness of the opportunity for the public to review the Third Order Draft of NCA4.

NCO staff also provided substantive updates on process and development directly to NCA authors in **weekly emails** and **monthly calls**. The broader public was kept abreast of developments through **regular updates** on the USGCRP website: http://www.globalchange.gov/nca4.

NCAnet Activities

USGCRP hosts an NCAnet (NCA network) Conversation on a roughly bimonthly basis (since January 2012). Briefly, NCAnet is a network of organizations working with the NCA to engage producers and users of assessment information across the United States. Participants (http://ncanet.usgcrp.gov/partners) help extend the reach of USGCRP assessment products, including the NCA and reports like the Climate and Health Assessment (https://health2016.globalchange.gov/), through the development of assessment-related capacities and products. These efforts have included collecting and synthesizing data or other technical and scientific information relevant to current and future assessments, disseminating findings to various users of assessment information, engaging assessment information producers and users, supporting assessment-related events, and producing communications materials related to the NCA and other assessment findings.

More information on NCAnet, including a list of NCAnet affiliates and presentations, as well as information on becoming a member, is available at http://ncanet.usgcrp.gov.

Regional Engagement Workshops and Subsequent Author Meetings

In order to gain feedback from the residents of the various NCA4 regions, author teams held workshops in various locations and invited members of the public and interested stakeholders to listen to presentations on the proposed chapter outlines. Attendees were then asked to provide feedback to authors to help clarify the priorities of the region, relay valuable technical inputs, and otherwise inform the development of the chapter. Reports from these workshops are available online at https://www.globalchange.gov/content/nca4-engagement-activities.

- Alaska Regional Engagement Workshop, Hub: Anchorage, Alaska, February 2017
- Northeast Regional Engagement Workshop, Hub: Boston, Massachusetts, with six satellite locations, February 2017
- Southwest Regional Engagement Workshop, Hub: Tucson, Arizona, with six satellite locations, February 2017
- Northern Great Plains Regional Engagement Workshop, Hub: Rapid City, South Dakota, with three satellite locations, February 2017
- Hawai‘i and U.S.-Affiliated Pacific Islands Regional Engagement Workshop, Hub: Honolulu, Hawai‘i, March 2017
- Midwest Regional Engagement Workshop, Hub: Chicago, Illinois, with nine satellite locations, March 2017
- Southern Great Plains Regional Engagement Workshop, Hub: Norman, Oklahoma, with one satellite location, March 2017

- U.S. Caribbean Regional Engagement Workshop, Hub: San Juan, Puerto Rico, with one satellite location, March 2017
- Southeast Regional Engagement Workshop, Hub: Raleigh, North Carolina, with seven satellite locations, March 2017
- Northwest Regional Engagement Workshop, Hubs: Portland, Oregon, and Boise, Idaho, March 2017

Listening Sessions

Listening sessions were held in a number of places where a full workshop was not appropriate or possible. Listening sessions included a brief overview presentation on the NCA, with some specifics on the chapters of interest to the given audience. Stakeholders were then encouraged to provide feedback on the content of the presentation, as well as any additional information or resources that might be useful for authors to understand.

- Great Lakes Adaptation Forum, October 2016, Ann Arbor, Michigan
- The Kresge Foundation, November 2016, Washington, DC
- American Geophysical Union Annual Meeting, December 2016, San Francisco, California
- American Meteorological Society Annual Meeting, January 2017, Seattle, Washington
- Transportation Research Board Aviation Climate Change Subcommittee, January 2017, Washington, DC
- National Council for Science and the Environment National Meeting, January 2017, Crystal City, Virginia
- Alaska Center for Climate Assessment and Policy Webinar, February 2017
- Association for the Sciences of Limnology and Oceanography, March 2017, Honolulu, Hawaiʻi
- National Adaptation Forum, May 2017, St. Paul, Minnesota

Presentations

Many presentations were given to relevant stakeholder audiences through the development of this report. An illustrative listing of NCA4-related presentations made by NCO staff includes:

- North American Carbon Program Science Leadership Group–NCA4 Overview, October 2016, Crystal City, Virginia
- Resilience AmeriCorps Federal Resource Fair, October 2016, Alexandria, Virginia
- 2016 Belmont Forum Plenary Meeting, November 2016, Doha, Qatar
- 7th Annual Northwest Climate Conference, November 2016, Stevenson, Washington
- American Lung Association, December 2016, Washington, DC
- American Geophysical Union Annual Meeting (NASA and NOAA booths), December 2016, San Francisco, California
- Transportation Research Board–Climate Change and Energy Task Force, January 2017, Washington, DC
- American Meteorological Society Annual Meeting Booth, January 2017, Seattle, Washington

- National Council for Science and the Environment Annual Meeting, January 2017, Crystal City, Virginia

- American Association for the Advancement of Science Annual Meeting, February 2017, Boston, Massachusetts

- 2017 Joint NACP Ameriflux Principal Investigators Meeting, March 2017, North Bethesda, Maryland

- Southeast & Caribbean Climate Community of Practice 2017 Meeting, April 2017, Charleston, South Carolina

- Association of State Floodplain Managers Annual Conference, May 2017, Kansas City, Missouri

- National Adaptation Forum, May 2017, St. Paul, Minnesota

- Conference of Mayors Annual Meeting, June 2017, Miami Beach, Florida

- Ecological Society of America Annual Meeting, August 2017, Austin, Texas

- American Chemical Society National Meeting, August 2017, Washington, DC

- Pacific Northwest Climate Conference, October 2017, Tacoma, Washington

- Geological Society of America Annual Meeting, October 2017, Seattle, Washington

- Guest lecture at Boston University, November 2017 (virtual)

- American Geophysical Union Fall Meeting, December 2017, New Orleans, Louisiana

- American Meteorological Society Annual Meeting, January 2018, Austin, Texas

- National Council for Science and the Environment Annual Meeting, January 2018, Crystal City, Virginia

- Guest lecture at San Francisco State University, February 2018 (virtual)

- National Association of Regulatory Utility Commissioners Winter Policy Summit, February 2018, Washington, DC

- Air and Waste Management Association webinar, February 2018 (virtual)

- American Association for the Advancement of Science Annual Meeting, February 2018, Austin, Texas

- Center for Climate and Energy Solutions Business Environmental Leadership Council Spring Meeting, March 2018, Washington, DC

- Guest lecture at University of Illinois, April 2018 (virtual)

- Guest lecture at University of Arizona, April 2018 (virtual)

- Electric Power Research Institute (EPRI) Energy 7 Climate Research Seminar, May 2018, Washington, DC

- Adaptation Futures Conference, June 2018, Cape Town, South Africa

- American Association of State Climatologists Annual Meeting, June 2018, Nebraska City, Nebraska

- National Academies of Sciences, Engineering, and Medicine Committee to Advise USGCRP, July 2018, Washington, DC

- Ecological Society of America Annual Meeting, August 2018, New Orleans, Louisiana

- National Academies of Sciences, Engineering, and Medicine Workshop on Subnational Climate Assessments, August 2018, Washington, DC

- Great Lakes Adaptation Forum, September 2018, Ann Arbor, Michigan

- Sigma Xi Annual Meeting, October 2018, Burlingame, California

- American Geophysical Union Fall Meeting, December 2018, Washington, DC

Sustained Assessment: Past, Present, and Future

The concept of, motivation for, and ideas to inform a sustained assessment process were articulated in Chapter 30 of NCA3, "Sustained Assessment: A New Vision for Future U.S. Assessments,"[26] and the NCADAC Special Report, "Preparing the Nation for Change: Building a Sustained National Climate Assessment Process."[27] In addition, the Interagency National Climate Assessment (INCA) Working Group provided thought leadership and implementation options in response to recommendations laid out in the above reports.

NCA4 was developed within a sustained assessment framework and process, drawing on these previous efforts, as well as an evaluation of the NCA3 process.[6] As part of this sustained assessment process, NCA4 built on and utilized products, indicators, and tools developed since NCA3 (many of which are described in detail in App. 3: Data & Scenarios). In addition, in response to gaps identified in NCA3, NCA4 is placed in a broader international context (detailed in the new chapter "Climate Effects on U.S. International Interests" and in the new appendix "Looking Abroad: How Other Nations Approach a National Climate Assessment"). The Climate Change Impacts and Risk Analysis (CIRA) project responds to a recommendation for additional work on quantifying the economic impacts of climate change across sectors of the American economy.[11] The CIRA report's project leaders not only provided information tailored to each NCA4 region and most sectors but also worked with many individual chapters through webinars, conference calls, and other collaborative interactions. Guidance on uncertainty and confidence treatment was also provided early on to NCA4 authors, responding to another sustained assessment recommendation.

While the aforementioned efforts provided a useful foundation on which NCA4 could be informed through a sustained assessment lens, greater efficiency and efficacy can be realized under a sustained assessment framework. In an effort to make that a reality, two groups were constituted to further elucidate what such a process could look like.

The **Advisory Committee for the Sustained National Climate Assessment (ACSNCA)** was a 15-member federal advisory committee established by the Department of Commerce on behalf of the USGCRP to advise SGCR on the sustained assessment process and stakeholder engagement. Its primary focus was not on NCA4 but on future assessment processes and engagement work around the NCAs. The ACSNCA met in person biannually and more frequently on teleconferences, with its first in-person meeting being held in September 2016. The original two-year charter for the ACSNCA expired in 2017 and was not renewed.

The **Sustained Assessment Interagency Working Group (SAWG)** provides an interagency forum for agencies to deliberate upon ideas for the various components composing a sustained assessment process. The SAWG holds monthly meetings attended by a diverse array of interagency experts, including SGCR Principals, USGCRP Interagency Working Group co-chairs and members, NCA4 Federal Steering Committee members, representatives from regional science organizations (for example, NOAA Regional Integrated Sciences and Assessments offices, DOI Climate Adaptation Science Centers, USDA Climate Hubs, etc.), and staff at the NCA4 Technical Support Unit. The SAWG first met in early 2017, when members began by reorienting themselves with the NCADAC recommendations and the options put forward by INCA. In ensuing months, thematic issues were discussed, bringing in outside experts to suggest ideas for next steps on a range of topics, including foundational elements, data tools and scenario products, special reports, user engagement, contributor engagement, harvesting assessments for research priorities, evaluation, and a vision and process for NCA5 and beyond.

The ultimate objective is to develop a process that includes activities inside and outside the Federal Government, makes efficient use of limited federal resources, and—importantly—is informed by and responsive to evolving user needs.

Acknowledgments

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On the Web: https://nca2018.globalchange.gov/chapter/appendix-1

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A2 Appendix 2. Information in the Fourth National Climate Assessment

The Fourth National Climate Assessment (NCA4) synthesizes information about the impacts of climate change in the United States. As a *highly influential scientific assessment* (HISA), information cited within NCA4 must meet the standards of the Information Quality Act (IQA).

Identification of Literature Sources

This report assessed information from several sources, including 1) technical input reports and scientific resources collected for the Third National Climate Assessment;[1] 2) the *Climate Science Special Report*[2] and other U.S. Global Change Research Program (USGCRP) science assessments; 3) a literature database comprising over 1,000 original reports meeting IQA requirements, compiled by USGCRP staff and shared with authors; 4) a public request for information released by the U.S. Department of Commerce in 2016;[3] 5) expert awareness of the literature from authors; 6) information provided during Regional Engagement Workshops and other engagement events;[4] and 7) chapter-specific submissions of technical resources and relevant literature to author teams.

The vast majority of sources used in this report are from peer-reviewed scientific literature. A library of relevant and significant peer-reviewed scientific literature was developed through a survey of scientific journals and through submissions collected via a Federal Register Notice (FRN). The FRN, published by the U.S. Department of Commerce on behalf of USGCRP on August 31, 2016, called for the public to submit "recent, relevant scientific and/or technical research studies including observed, modeled and/or projected climate science information that have been peer-reviewed and published or accepted for publication in scientific journals and/or government reports."[3] In addition, the FRN called for submission of information outside the scientific peer-reviewed literature, such as reports produced by nonprofit communities, but it noted that all information used in the report would need to comply with the IQA.

In addition, USGCRP hosted Regional Engagement Workshops in each of the 10 NCA4 regions, and several author teams hosted chapter-specific webinars or events (see App. 1: Process for additional details).[4] Each of these events enabled the public to provide author teams with additional resources and information. As follow-up to these events, the public had access to chapter-specific email addresses to submit further resources to chapter author teams.[4]

Compliance with the Information Quality Act

During the chapter development process, author teams assessed the available literature (see individual chapter Traceable Accounts for additional details). Guidance on information quality was provided to the author teams to assist in this process, directing the author teams to rely primarily on peer-reviewed scientific literature.

In limited situations where information was available only outside peer-reviewed scientific literature or U.S. Government reports, author teams were provided with a decision tree to aid them in evaluating potential sources by addressing the following considerations:

- **Utility:** Is the particular source important to the topic of your chapter?
- **Transparency and traceability:** Is the source material identifiable and publicly available?
- **Objectivity:** Why and how was the source material created? Is it accurate and unbiased?
- **Information integrity and security:** Will the source material remain reasonably protected and intact over time?

As the administrative agency responsible for producing this report, the National Oceanic and Atmospheric Administration ensured that all referenced information adhered to its Information Quality Guidelines.[5]

Acknowledments

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A3 Appendix 3. Data Tools and Scenario Products

Introduction

To enable National Climate Assessment (NCA) authors to do the in-depth analysis necessary to make the Fourth National Climate Assessment (NCA4) most useful, the U.S. Global Change Research Program (USGCRP) provided author teams with an array of data tools and scenario products. This appendix contains additional information on some of the materials available to NCA4 authors in developing their chapters. While designed in part with NCA4 authors in mind, this suite of "Tools for Informed Decision-Making" is intended to support the day-to-day work of resource managers, community planners, and scientists across the country.

Tools Within the Sustained Assessment Process

Since the completion of the Third National Climate Assessment (NCA3) in 2014,[1] a major focus of work among USGCRP and its affiliated agencies has been to establish a process to continually add to and improve the knowledge and resources available to decision-makers seeking to address climate risks. The motivation for and benefit from that process is to evolve the NCA from being a periodic snapshot of the state of climate science into a sustained effort that is not only responsive to changing conditions but also allows for the continuing incorporation of newly developed products and research. Beyond being useful for NCA4 authors, these tools also represent a mechanism for ongoing development and updating of materials. Such a continuous process could make assessment products more valuable for connecting research with decision-making, thus facilitating evaluation of the state of knowledge and establishing rigorous ways of documenting and responding to changes over time.

Scenario Products

Scenarios are coherent, internally consistent, and plausible descriptions of possible future states of the world. Scenarios may be quantitative, qualitative, or both. The components of a scenario are often linked by an overarching logic, such as a qualitative narrative of how the future may evolve.

Overview

The USGCRP is mandated to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." To fulfill this mandate, the NCA evaluates risks that climate and global change pose to the United States. This entails addressing specific questions about what is at risk in a particular region or sector and how it might be affected in different potential futures. Scenarios that span a range of plausible future changes in key environmental parameters, such as weather and climate extremes, sea level, population, and land use, can help carry this out. USGCRP has therefore coordinated the development of a set of scenario products, accessible at https://scenarios.globalchange.gov/, to support NCA4 development. Specifically, NCA4 authors have been provided with a suite of high-resolution (downscaled) scenario products for the United States, covering (at least) the entire 21st century, to support chapter development.

Selection of Representative Concentration Pathways

NCA4 authors have grounded their assessment in an analysis of the widely used scenarios termed "Representative Concentration Pathways," or RCPs, that form the foundation for the majority of recent coordinated global climate model experiments. (RCPs are also discussed in this report's Front Matter.) Consistent with previous NCAs, NCA4 relies in part on climate scenarios and modeling efforts generated for the Intergovernmental Panel on Climate Change (IPCC) assessments. In May 2015, USGCRP released a memo outlining the decisions regarding climate-related scenarios and the rationale around them.[2] Specifically, USGCRP decided to use the RCPs[3,4] and associated model results from the Climate Model Intercomparison Project Phase 5 (CMIP5)[5] that underpinned the IPCC 5th Assessment Report (AR5), completed in 2013–2014.

The CMIP model results, as driven by the RCP scenarios, have similarly become standard reference inputs for virtually all work in the United States and internationally concerning climate change science, impacts, vulnerability, adaptation, and mitigation. It is, therefore, reasonable, practical, and in line with the expectations of the research community for NCA4 to use the most recently available model outputs from CMIP5, associated with the RCPs. CMIP5 climate data were widely available during the development of NCA4; products from the next phase of the CMIP project (CMIP6) were not available in time to support NCA4.

USGCRP further decided that NCA4 would focus primarily on RCP8.5 and RCP4.5 for framing purposes, while also considering other scenario information where appropriate (for example, RCP2.6). These RCPs capture a range of plausible atmospheric concentration futures that drive climate models. RCP8.5 is the high-end scenario (high emissions, high concentrations, large temperature increase) in the IPCC's AR5; it likewise serves as the high-end scenario for NCA4, similar to the use of IPCC's 4th Assessment Report (AR4) Special Report on Emissions Scenarios (SRES) A2 scenario in NCA3.[6] RCP4.5 is not the lowest scenario in AR5, but it is similar to the AR4 SRES low-end B1 scenario that was used in NCA3. RCP2.6 represents the low end of the range considered by AR5, but it also assumes significantly greater emissions reductions, even for current and near-term emissions, than previous low-end scenarios used by the IPCC. The range represented by RCP8.5 and RCP4.5, therefore, provides the most continuity and consistency with the IPCC scenarios used for framing purposes by the previous NCA3.

As simulated in CMIP5, all of the RCPs result in similar global temperature and sea level rise outcomes for the next few decades. However, by mid-century and beyond, differences between RCPs have a substantial effect on the climate and impact outcomes (see Ch. 2: Climate, Figure 2.2). The choice to focus on RCP8.5 and RCP4.5 for impacts, adaptation, and vulnerability analyses allows for an evaluation of near-term concerns for the Nation, as well as a robust and wide range of longer-term outcomes relative to the present.

Because RCPs intentionally focus on the outputs that are in turn fed into climate models (namely atmospheric concentrations), a wide range of future assumptions about underlying socioeconomic conditions, both at the global and national scale (for example, population growth, technological innovation, and carbon intensity of the energy mix), could plausibly be consistent with each of the RCPs used in NCA4. For this reason, further guidance on U.S. population and land-use assumptions was provided to authors, as discussed in the Products section of this chapter. Nevertheless, each RCP was developed by a separate modeling team;[4] for illustration, some of the assumptions in those modeling runs include the following:

- The range of future global population projections within the RCPs falls within the range of the low and high United Nations population projections from 2003.
- The range of global gross domestic product (GDP) projections within the RCPs falls within the range of the 90th-percentile range of GDP scenarios found in the literature available prior to publication of the RCPs.
- RCP2.6, RCP4.5, and RCP6.0 represent intermediate scenarios from the literature, resulting in primary energy use of 750 to 900 EJ (exajoules) in 2100 or about double recent levels; RCP8.5 is a much more energy-intensive scenario.
- Because of assumptions about future viability of carbon capture and storage (CCS) technologies, *all* scenarios use greater amounts of coal and/or natural gas than in the year 2000.
- An important element of RCP2.6 is the use of bio-energy in combination with CCS, resulting in negative emissions by the end of century.
- All RCPs assume increasingly stringent air pollution control policies.

Comparing outcomes under RCP8.5 with those of RCP4.5 (and RCP2.6 in some cases) not only captures a range of uncertainties and plausible futures but also provides information about the potential benefits of mitigation. Comparing outcomes under the two pathways shows the degree to which significant emissions mitigation at the global scale can avoid some impacts and inform adaptation choices to the risks that are present even at the low-end scenario. The scenario range allows for an assessment of impacts at a variety of temperature thresholds.

Products

Overview

As noted earlier, NCA4 authors were provided with a suite of high-resolution (downscaled) scenario products for the United States, covering at least the entire 21st century, to assist them in the development of their chapters (hosted at https://scenarios.globalchange.gov). These included

- changes in the averages and extremes of key climate variables (for example, temperature and precipitation),
- relative sea level rise along the entire U.S. coastline,
- population change as a function of demographic shifts and migration, and
- changes in developed land use driven by these population changes.

Authors were encouraged to use the provided scenario products to help ensure consistency in underlying assumptions and to improve the ability to compare and synthesize across chapters. Authors used these scenario products to frame uncertainty in future climate as it related to the regional and sectoral risks that were the focus of their chapters—both uncertainty as a result of considering multiple RCPs and uncertainty due to limitations in our understanding of key climate system processes or our ability to fully represent these processes in earth system models.

To better assist the author teams in meeting their needs, and to reduce the potentially large volume of underlying scenario products from which the authors could potentially draw, NCA4 authors were encouraged to think of the scenario products as being grouped into the following three USGCRP scenarios: "Lower," "Higher," and "Upper Bound" departures from current conditions (Table A3.1).

For example, given this assessment's emphasis on using a risk-based framework, authors were asked to consider low-probability, high-consequence climate futures. Addressing this potential future, in addition to more probable futures, is facilitated by considering the Upper Bound USGCRP scenario. These outcomes will often pose the greatest risks to society and thus must be considered in any comprehensive risk assessment.

Similarly, the authors were asked to consider how future trends in other critical, non-climatic stressors, including population growth and land-use change, may interact with climate change to exacerbate (or alleviate) climate-related risks. Authors have, therefore, been provided with scenarios of these additional drivers, grouped with the climate-related scenarios under the Lower, Higher, and Upper Bound USGCRP scenarios (see Ch. 17: Complex Systems for additional discussion on how non-climatic stressors can exacerbate climate-related risks).

Authors have used these scenario products to support a range of tasks within individual NCA4 chapters. Many chapters use scenario products for broad needs, such as general context-setting to illustrate a range of possible future outcomes in key drivers of risk and determinants of vulnerability. Others have applied them to bound the envelope of scientifically plausible future climate change in assessing regional or sectoral risks. Still others have used scenarios to place existing literature into the context of a consistent, coordinated set of possible future conditions in order to facilitate improved synthesis. All of these applications are valuable uses of these scenario products for both the NCA and its users.

USGCRP Scenarios

Scenario Inputs	Lower Scenario	Higher Scenario	Upper Bound Scenario
temperature means/extremes	RCP4.5 ensemble mean	RCP8.5 ensemble mean	95th percentile of RCP8.5
precipitation means/extremes	RCP4.5 ensemble mean	RCP8.5 ensemble mean	95th percentile of RCP8.5
sea level rise	"Intermediate-Low"	"Intermediate"	"Extreme"
population	"lower" (SSP2)	"higher" (SSP5)	"higher" (SSP5)
development land use	"lower" (SSP2)	"higher" (SSP5)	"higher" (SSP5)

Table A3.1: Scenario products are organized into three USGCRP scenarios based on their departure from current conditions. The Shared Socioeconomic Pathways (SSPs) are described in greater detail later in this chapter.

Downscaled Climate Information

Driven by stakeholder feedback and input seeking information about potential future climate change at much finer spatial scales than is typically generated by the state-of- the-art global climate models (which have horizontal resolutions on the order of 100 km, or about 62 miles), NCA4 authors were provided with CMIP5 model outputs that had been downscaled to finer scales using the LOcalized Constructed Analogs (LOCA) methodology.[7]

The LOCA method is a statistical technique to downscale climate model output to a smaller spatial scale, providing a much finer geographical resolution for analysis. In the LOCA method, the local simulated climate model field for each day is matched to examples in historical observations that resemble the climate model spatial distribution, called analog days. Since historical observations are sufficiently dense to represent local features, the resulting dataset provides a realistic representation of the local variability suitable for many impacts analyses.

Previous methods that utilized the same basic approach identified a set of days (typically 30) that resemble the climate model field over a large region and produced the downscaled field through an optimal weighting of the entire set of analog days.[8] The LOCA method improves on these earlier methods in several ways. First, the analog days are chosen separately for local regions, thus providing a more realistic choice of analog days at the local scale. Second, for most of the local region, the single analog day best matching the climate model simulation is used for downscaling, rather than averaging a set of days. This produces a better representation of extreme events.

The LOCA data include 32 CMIP5 models covering the 1950–2100 period, including the historical period of 1950–2005, as well as a higher scenario (RCP8.5) and a lower scenario (RCP4.5) for 2006–2100. The LOCA data include maximum temperature, minimum temperature, and precipitation at a daily resolution and at 1/16th-degree spatial resolution. The spatial coverage is the continental United States, southern Canada, and northern Mexico. LOCA data were not completely available for the U.S. Caribbean, Alaska, or Hawaiʻi and U.S.-Affiliated Pacific Islands regions for NCA4, but extending LOCA to include these locations is an area of active research.

Sea Level Rise Scenarios

The Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Task Force, a joint task force of the National Ocean Council (NOC) and USGCRP, was charged with developing and disseminating future sea level rise and associated coastal flood hazard scenarios and tools for the entire United States to support coastal preparedness planning and risk management processes.

Two key subtasks of the overall Task Force effort were to 1) develop updated scenarios of global mean sea level (GMSL), and 2) regionalize these global scenarios for the entire U.S. coastline, to serve both as inputs into assessments of potential vulnerabilities and risks in the coastal environment and as key technical inputs into NCA4. In order to bound the set of GMSL rise scenarios for year 2100, the Task Force assessed the most up-to-date scientific literature on scientifically supported upper-end GMSL projections, including recent observational and modeling literature related to the potential for rapid ice melt in Greenland and Antarctica.

Global Mean Sea Level Rise Scenarios

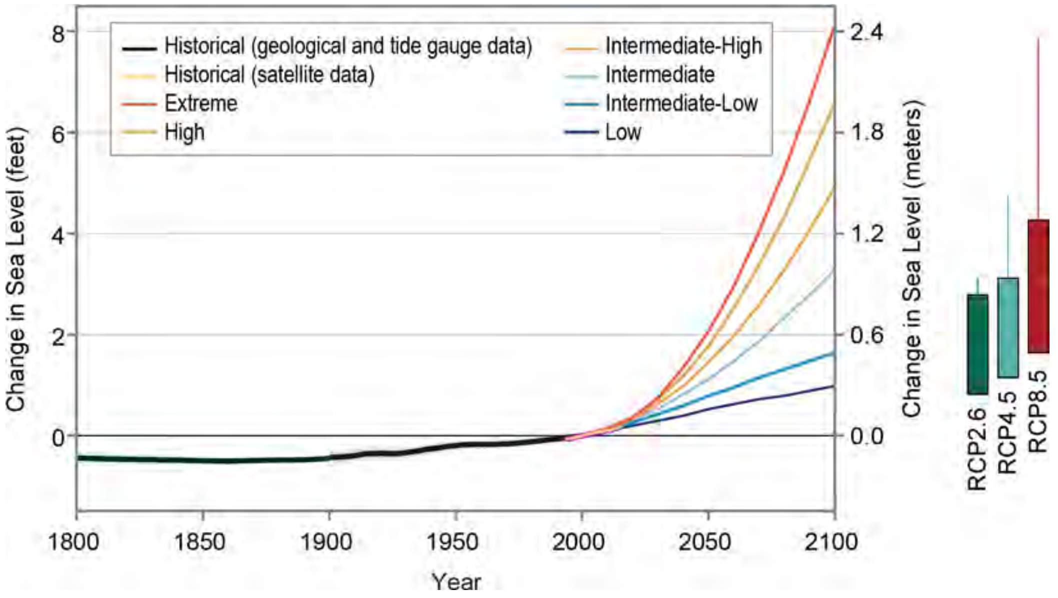

Figure A3.1: The figure shows observed (black and orange lines) and projected changes in global mean (average) sea level rise for 1800–2100. The projected changes are from six global average sea level scenarios developed for an interagency technical report.[9] The boxes on the right show the *very likely* ranges in sea level rise by 2100 (relative to 2000) corresponding to the three different RCP scenarios. The lines above the boxes show possible increases based on the newest research of the potential contribution to sea level rise from Antarctic ice melt. Source: Ch. 2: Climate, Figure 2.3, adapted from Sweet et al. 2017.[9]

This projected GMSL range was discretized into six GMSL rise scenarios at 0.5-meter increments (Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme, which correspond to a GMSL rise of 0.3 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m, respectively, by 2100). These were then used as the basis for deriving relative sea level (RSL) rise on a 1-degree grid covering the coastlines of the U.S. mainland, Alaska, Hawai‘i, the U.S. Caribbean, and the U.S.-Affiliated Pacific Islands regions, as well as at the precise locations of available tide gauges along these coastlines. The RSL values account for key factors important at regional scales, including 1) shifts in oceanographic factors; 2) changes in Earth’s gravitational field and rotation, and flexure of the crust and upper mantle due to melting of land-based ice; and 3) non-climatic factors mostly associated with vertical land movement (subsidence or uplift) due to glacial isostatic adjustment (the continuing vertical movement of land in response to the melting of the ice cover from the last ice age), sediment compaction, and groundwater and fossil fuel withdrawals.

These global and regional/local scenario products are available for the 2000–2100 period at 10-year intervals and over 2100–2200 at a coarser temporal resolution (the scenario values are provided for 2120, 2150, and 2200).

Population and Land-Use Scenarios

Population and land-use scenarios for NCA4 have been developed through the U.S. Environmental Protection Agency’s (EPA) Integrated Climate and Land Use Scenarios (ICLUS) effort. ICLUS explores future changes in human population and developed land use for the contiguous United States. These projections are broadly consistent with peer-reviewed storylines of population growth and economic development that are now widely used by the climate change impacts community.[10] Specifically, the different population and land-use change scenarios stem from global population and urbanization assumptions underlying two different future trajectories from the Shared Socioeconomic Pathways (SSPs) effort:[11] SSP2, which represents a business-as-usual trajectory, similar to the U.S. Census population projection (out to 2060), and SSP5, which represents a trajectory with higher fertility and higher net migration into the United States.[12] At the global scale, socioeconomic assumptions under SSP2 are broadly consistent with the concentration pathway and resultant radiative forcing for RCP4.5, whereas the socioeconomic assumptions under SSP5 are more consistent with RCP8.5.

ICLUS data (version 2) outputs have been made available to NCA4 authors (including training webinars) and consist of both population and land-use projections. Two ICLUS projections are provided. These are based on the 2010 U.S. Census and use fertility, mortality, and immigration rates from the Wittgenstein Centre to project decadal population to 2100, consistent with the demographic assumptions of the SSP2 and SSP5 socioeconomic scenarios, respectively.

These ICLUS population projections are used as inputs to a land-use model, which spatially allocates five residential land uses (exurban-low, exurban-high, suburban, urban-low, and urban-high) as well as commercial and industrial uses.

Indicators

Overview

The USGCRP hosts an interagency climate-related indicator platform at http://www.globalchange.gov/browse/indicators. Climate indicators for this purpose are defined as observations or other measures that are used to track the state of or the trend in conditions with a scientifically based relationship to the changing climate. For example, businesses might look at the unemployment index as one of a number of indicators representing the condition of the economy. Similarly, indicators related to climate—which may be physical, ecological, or societal—can be used to understand how environmental conditions are changing, to assess risks and vulnerabilities, and to help inform resilience and planning for climate impacts.

One of the primary goals of the USGCRP indicators effort is to support a sustained National Climate Assessment process by regularly tracking variables relevant to climate change. USGCRP and its participating agencies intend to maintain the indicators as a living resource, routinely updating them with new data. In addition, the indicators effort serves as a platform for USGCRP agencies to showcase data collection efforts and to highlight research related to indicators of change across a range of sectors.

The USGCRP indicators are not intended to be representative of all potential indicators across all possible scales; rather, they are meant to communicate several key aspects of climate change, such as temperatures over land and at sea, greenhouse gas (GHG) levels in the atmosphere, the extent of arctic sea ice, and related effects in sectors like public health, water resources, and agriculture. All of the indicators show climate-related trends over time and meet established criteria related to data quality.[13] Similar to the findings and figures in NCA3 and other NCA reports and products, the indicators' underlying datasets are documented in USGCRP's Global Change Information System (GCIS).

USGCRP Indicators

USGCRP's indicator platform currently includes 15 representative global and national-level climate indicators:[14]

- annual GHG index
- arctic glacial mass balance

- arctic sea ice extent
- atmospheric carbon dioxide
- frost-free season
- global surface temperatures
- heating and cooling degree days
- heavy precipitation
- ocean chlorophyll concentrations
- sea level rise (global)
- sea surface temperatures
- start of spring
- terrestrial carbon storage
- U.S. heat waves
- U.S. surface temperatures

Additional Indicator Resources

Several U.S. federal agencies make available climate-relevant indicators and their underlying data. For example, the EPA partners with more than 40 data contributors from various government agencies, academic institutions, and other organizations to compile a key set of nearly 40 indicators related to the causes and effects of climate change. The indicators are published in the EPA's report *Climate Change Indicators in the United States*. Updated datasets can be found on the EPA website.[17] To provide a more comprehensive resource to NCA4 authors and the broader public, readers can access a much more expansive suite of climate indicators, many at a regional scale, here: https://www.epa.gov/climate-indicators.

The EPA's climate indicators effort is meant to communicate the causes and effects of climate change in the areas of atmospheric composition, weather and climate, oceans, snow and ice, health and society, and ecosystems. All of the indicators are based on historical observations (no projections), are independently peer-reviewed, and are routinely updated with new data.

A variety of other readily accessible federal climate indicator resources are available for public use, including

- Centers for Disease Control and Prevention's (CDC) National Environmental Public Health Tracking network: https://ephtracking.cdc.gov/showClimateChangeIndicators,
- EPA's U.S. Inventory of Greenhouse Gas Emissions and Sinks: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks,
- National Aeronautics and Space Administration's (NASA) Global Climate Change: Vital Signs of the Planet: https://climate.nasa.gov/,
- National Oceanic and Atmospheric Administration's (NOAA) Arctic Program, Arctic Report Card: http://www.arctic.noaa.gov/Report-Card, and
- NOAA's State of the Climate: https://www.ncdc.noaa.gov/sotc/.

Other relevant sources of indicator information include

- NOAA's State Summaries: stateclimatesummaries.globalchange.gov, and
- USGCRP's *Climate Science Special Report*: https://science2017.globalchange.gov/.[18]

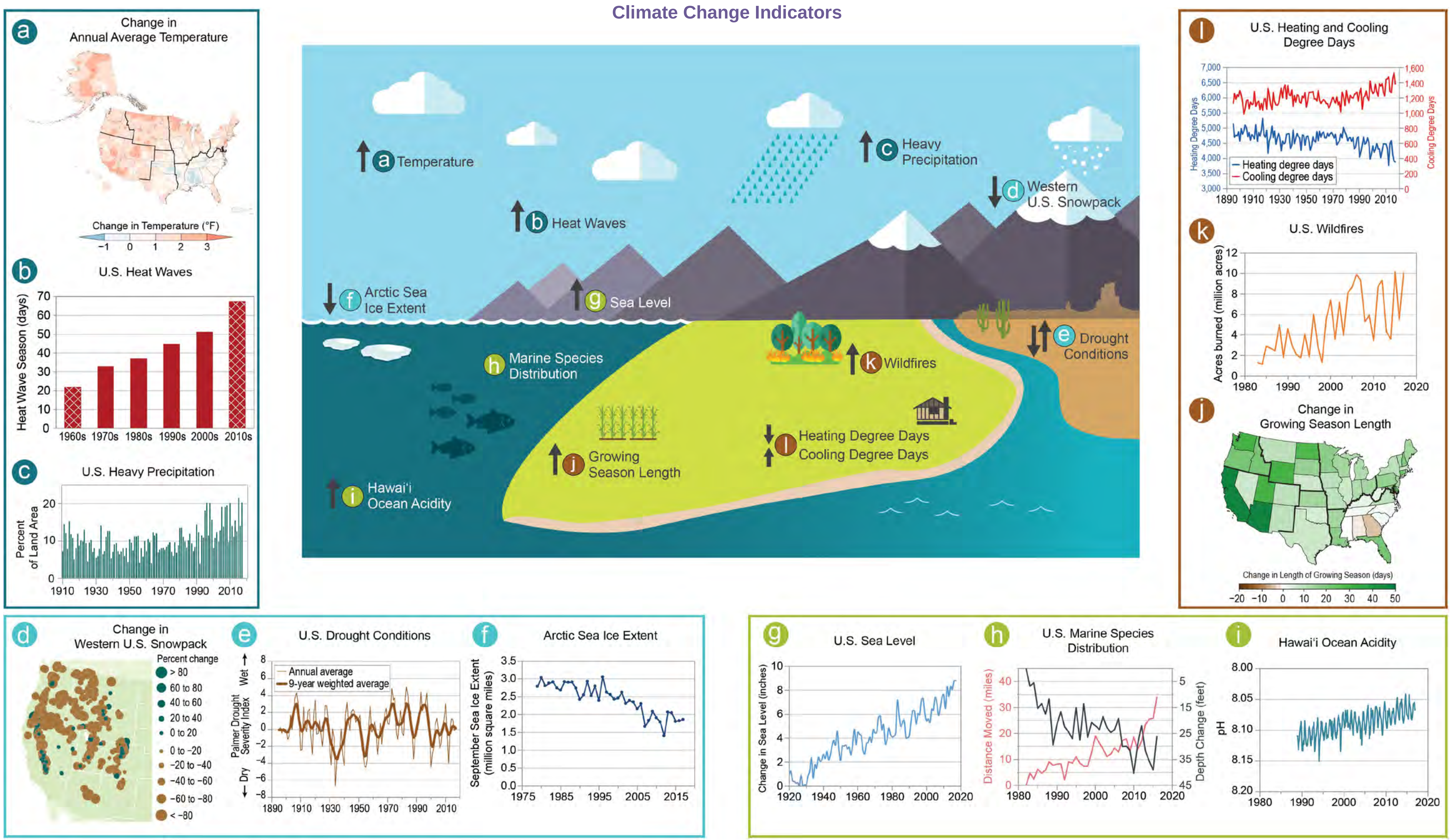

Figure A3.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change based on data collected across the United States. Upward-pointing arrows indicate an increasing trend; downward-pointing arrows indicate a decreasing trend. Bidirectional arrows (for example, for drought conditions) indicate a lack of a definitive national trend. (Figure caption continued on next page)

Atmosphere (a–c): (a) Annual average temperatures have increased by 1.8°F across the contiguous United States since the beginning of the 20th century; this figure shows observed change for 1986–2016 (relative to 1901–1960 for the contiguous United States and 1925–1960 for Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands). Alaska is warming faster than any other state and has warmed twice as fast as the global average since the mid-20th century (Ch. 2: Climate, KM 5; Ch. 26: Alaska, Introduction). (b) The season length of heat waves in many U.S. cities has increased by over 40 days since the 1960s. Hatched bars indicate partially complete decadal data. (c) The relative amount of annual rainfall that comes from large, single-day precipitation events has changed over the past century; since 1910, a larger percentage of land area in the contiguous United States receives precipitation in the form of these intense single-day events.

Ice, snow, and water (d–f): (d) Large declines in snowpack in the western United States occurred from 1955 to 2016. (e) While there are a number of ways to measure drought, there is currently no detectable change in long-term U.S. drought statistics using the Palmer Drought Severity Index. (f) Since the early 1980s, the annual minimum sea ice extent (observed in September each year) in the Arctic Ocean has decreased at a rate of 11%–16% per decade (Ch. 2: Climate, KM 7).

Oceans and coasts (g–i): (g) Annual median sea level along the U.S. coast (with land motion removed) has increased by about 9 inches since the early 20th century as oceans have warmed and land ice has melted (Ch. 2: Climate, KM 4). (h) Fish, shellfish, and other marine species along the Northeast coast and in the eastern Bering Sea have, on average, moved northward and to greater depths toward cooler waters since the early 1980s (records start in 1982). (i) Oceans are also currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually by human activities, increasing their acidity (measured by lower pH values; Ch. 2: Climate, KM 3).

Land and ecosystems (j–l): (j) The average length of the growing season has increased across the contiguous United States since the early 20th century, meaning that, on average, the last spring frost occurs earlier and the first fall frost arrives later; this map shows changes in growing season length at the state level from 1895 to 2016. (k) Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and Interior Alaska over the past several decades.[15] (l) Degree days are defined as the number of degrees by which the average daily temperature is higher than 65°F (cooling degree days) or lower than 65°F (heating degree days) and are used as a proxy for energy demands for cooling or heating buildings. Changes in temperatures indicate that heating needs have decreased and cooling needs have increased in the contiguous United States over the past century. Sources: (a) adapted from Vose et al. 2017,[16] (b) EPA, (c–f and h–l) adapted from EPA 2016,[17] (g and center infographic) EPA and NOAA.

Climate Resilience Toolkit

In NCA3, authors used case studies to highlight specific examples of work being done by regions, cities, and stakeholders throughout the United States. These case studies formed some of the basis for the development of the U.S. Climate Resilience Toolkit (CRT).

The CRT is a free, open-source website (https://toolkit.climate.gov/) designed to help communities and businesses build resilience to climate-related impacts and extreme events. Its primary target audience is applied professionals—including city planners, resource managers, policy leaders, facility managers, analysts, and consultants—who oversee or help guide the development and implementation of climate adaptation plans. The site is easily understandable and is also accessible to the general public, a secondary target audience.

Published in November 2014, the CRT was developed as an interagency partnership under the auspices of the USGCRP. Hosted and managed by NOAA, it is a web-based framework that aggregates and contextualizes scientific information, tools, and expertise to help people

1. make and implement climate adaptation plans;
2. explore how climate conditions are changing in their location and understand how their valued assets are, or may be, impacted;
3. learn what others are doing to address climate-related challenges similar to the ones they face; and
4. learn about funding sources that can help in disaster recovery and/or to mitigate future risks.

Case studies (https://toolkit.climate.gov/#case-studies) have also been incorporated as a feature of NCA4, and some of those studies will be incorporated into the CRT in the future.

Steps to Resilience

The CRT's "Steps to Resilience" is the site's centerpiece (https://toolkit.climate.gov/#steps). It is a five-step, iterative risk-management framework that integrates a range of different content types into topical, geographical, and purposeful frames of reference.

This framework guides users through a deliberative process whereby they can access, explore, discuss, co-produce, and integrate information to build shared mental models as they address several fundamental questions:

1. Do climate-related hazards threaten assets we value?
2. If so, what is the risk, and are we willing to tolerate that level of risk?
3. If the risk is intolerable, what options exist to reduce or eliminate the risk?
4. Which options are viable and affordable, and in what priority order might we pursue them?
5. How will we plan and implement particular actions?

To help users answer these questions, the Toolkit offers plain language narratives—excerpted from the NCAs and other authoritative sources—that summarize ways that U.S. sectors, regions, and built and natural environments are vulnerable to, and have been impacted by, climate and non-climate stressors. These narratives are cross-linked with over 110 real-world case studies, from across the United States and its territories, highlighting people in communities and businesses who have successfully taken action to manage their climate risks. Additionally, the site's narratives and case studies are cross-linked with science-based decision support tools to illustrate how people have used those tools to plan and build resilience.

CRT Tools and the Climate Explorer

The CRT's "Tools" compendium (https://toolkit.climate.gov/tools) has more than 400 decision support tools offering a wide range of functions, such as helping people identify their vulnerabilities, view past and present climate conditions, download and analyze data, engage and communicate, check applied forecasts, find adaptation planning support, recover and rebuild from a disaster, and visualize climate projections.

The "Climate Explorer" (https://toolkit.climate.gov/#climate-explorer) is the CRT's featured tool for visualizing climate projections. Maps and graphs are available for 20 decision-relevant variables (such as temperature, precipitation, and heating- and cooling-degree days) for every county in the contiguous United States. Users can compare observed historical data to hindcasts (a method of testing a model for future events by comparing predictions of past events to known data) for the 1950–2006 period, and they can explore the projected rates and magnitudes of change in two future scenarios (RCP4.5 and RCP8.5) from 2006-2100.

Climate Explorer version 2.6, published in May 2018, features these improvements:

- replaced the Bias Corrected Constructed Analogs (BCCA) with the LOcalized Constructed Analogs (LOCA) projection dataset to align with the NCA4;

- added about 90 tidal stations charting both historical observed and future projected annual number of days with high tide flooding;
- enabled users to visually compare future projections to observed historical maps (1961–1990);
- added a new module enabling users to select specific thresholds for select locations to produce annual counts of observed threshold exceedance over time; and
- transitioned the tool's map library from OpenLayers to the ArcGIS Javascript library to make it interoperable with Esri's "ArcGIS Living Atlas of the World."

The CRT evolved and expanded in 2017 to include regional sections, enhancements to link more closely with the Steps to Resilience, and an expanded menu of climate variables offered in the Climate Explorer.

Climate Resilience Toolkit Case Study Categories

Climate Threat/Stressors	Topics	Resilience Steps	Regions
• Sea level rise, storm surge, and coastal flooding • Drought • Extreme precipitation • General climate change • Extreme events • Increased temperatures • El Niño, La Niña, and climate variability • Flooding • Changes in growing seasons • Changing ocean conditions • Reduced sea ice, permafrost, and snow • Temperature extremes	• Coasts • Built environment • Water • Ecosystems • Health • Food • Tribal nations • Marine • Energy • Transportation	1. Explore climate threats 2. Assess vulnerability and risks 3. Investigate options 4. Prioritize actions 5. Take action	• Southwest • Northeast • Southeast • Midwest • Alaska • Northwest • Hawai‘i and U.S.-Affiliated Pacific Islands • Great Plains • International • National

Table A3.2. The CRT contains over 140 case studies, which users can quickly filter to locate a story of interest using the menu filters listed above.

Climate Resilience Toolkit Decision Support Tools

Topic	Tool Function
• Coasts • Built environment • Water • Ecosystems • Health • Food • Tribal nations • Marine • Energy • Transportation	• Identify vulnerabilities • View past and current conditions • Analyze and download data • Engage and communicate • Find adaptation planning support • Check applied forecasts • Recover and rebuild • Visualize climate projections

Table A3.3: The CRT contains over 400 decision support tools, and users can filter by topic, function, U.S. region, and the Steps to Resilience.

Global Change Information System

Summary

The National Climate Assessment and Development Advisory Committee (NCADAC), which guided the development of NCA3, recommended in 2013 that the NCA process "manage data to maximize utility and transparency."[19] The report also highlighted the importance of "developing a comprehensive web-based system to deploy and manage global change information and present it in a way that can be used by and benefit scientists, the public, and decision-makers." To achieve these goals, the USGCRP established the Global Change Information System (GCIS).

The GCIS is an open-source centralized database of all materials and data used for USGCRP assessments (https://data.globalchange.gov/). The system acts as an advanced, multifaceted bibliography, maintaining traceable provenance records of scientific information and providing access to the original data and research. The GCIS catalogs the cross-links among research papers, researchers, original data, and more and includes links back to authoritative sources for its information. GCIS serves as a key supporting resource for assessments produced by the USGCRP, providing information about the data underpinning them. In addition, the GCIS guides users to global change research produced by the 13 USGCRP member agencies.

Identifiers

Each item (for example, a report, dataset, or organization) referenced in the GCIS has a unique, persistent identifier. When possible, this includes or is related to third-party identification systems, such as Universally Unique Identifiers (UUIDs), Digital Object Identifiers (DOIs), Open Researcher and Contributor Identifiers (ORCIDs), and International Standard Book Numbers (ISBNs). This enhances interoperability between the GCIS and other information systems. For resources where such persistent identifiers are unknown, GCIS creates its own, and links between resources are assigned using the identifiers so that edits and corrections made to resource names or other properties do not break data linkages.

Provenance and Semantics

GCIS is built to represent the provenance of information contained in government assessments about global environmental change. GCIS includes in this (following the World Wide Web Consortium's definition of provenance) "information about entities, activities, and people involved in producing a piece of data or thing, which can be used to form assessments about its quality, reliability or trustworthiness."[20] This information is captured by a combination of documentation by the authors and scripts that ingest machine-readable metadata from online catalogs. Resources in GCIS are related both in relational databases, for cases of ownership (for example, a chapter belongs to a report and doesn't exist independently), and in a database that represents semantically the nature of the relationship between two resources (for example, a report *cites* a book, a table *is derived from* a dataset).

Traceability and Provenance in GCIS

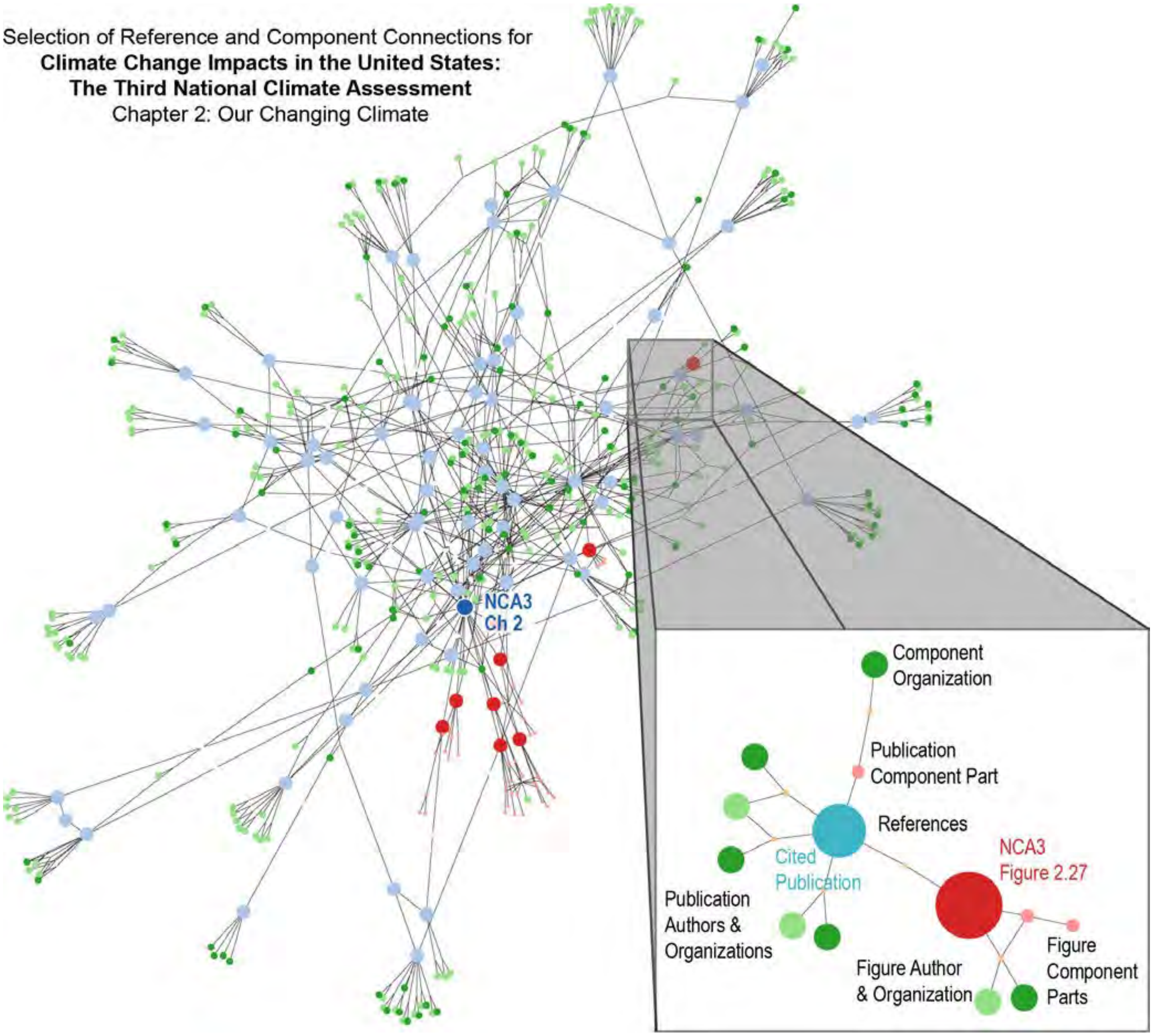

Figure A3.3: This figure is a graphic representation of traceability and provenance within the Global Change Information System (GCIS). All records within GCIS seek to have each component of this chain tracked and available to any reader. Tracking each of these components allows for any interested member of the public to trace a conclusion back to the supporting data for that conclusion. Source: USGCRP.

NOAA State Climate Summaries

Overview

NOAA produced a set of State Climate Summaries in response to a growing demand for state-level information after the release of NCA3 (stateclimatesummaries.globalchange.gov). These summaries consist of observed and projected climate change information and focus on aspects that are part of NOAA's mission (mainly, characteristics of the physical climate and coastal issues). These state summaries support various aspects of chapters throughout NCA4 and, deriving from the charge in the Global Change Research Act of 1990, contain information both on historical trends and scientific knowledge about potential future trends.

While the datasets and simulations in these state summaries are not by themselves new (they have been previously published in various sources), these documents represent a targeted synthesis of historical and plausible future climate conditions for each state.

Each summary consists of several high-level Key Messages about how climate change has or is likely to affect that state, as well as a description of the historical climate conditions in the state and of the climate conditions associated with future pathways of GHGemissions. In addition to this consistent information across all the state summaries, each summary contains some degree of state-specific information, making it uniquely valuable to decision-makers across the respective state. All 50 summaries (plus one for Puerto Rico and the U.S. Virgin Islands) underwent an anonymous external review, with at least two expert reviews completed per state.

Historical Climate

The description of historical climate conditions for each state is based on an analysis of core climate data (the data sources are described in the supplementary online material for the summaries). However, to help understand, prioritize, and describe the importance and significance of different climate conditions, additional input was derived from climate experts in each state, some of whom are authors on these state summaries. In particular, input was sought from the NOAA Regional Climate Centers and from the State Climatologists. The historical climate conditions are meant to provide a perspective on what has been happening in each state and what types of extreme events have historically been noteworthy and to provide a context for the assessment of future impacts.

Future Scenarios

Future climate scenarios are intended to provide an internally consistent set of climate conditions that can inform analyses of potential impacts of climate change under certain assumptions about the future pathway of GHG emissions. Here, "consistent" means that the relationships among different climate variables and the spatial patterns of these variables derive directly from the same set of climate model simulations and are, therefore, physically plausible. The future climate scenarios are based on well-established sources of information (see the Scenario Products section of this appendix). No new climate model simulations or downscaled datasets were produced for use in the state summaries.

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On the Web: https://nca2018.globalchange.gov/chapter/appendix-3

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A4 Appendix 4. Looking Abroad: How Other Nations Approach a National Climate Assessment

Introduction

The U.S. National Climate Assessment (NCA) is far from the only national assessment of climate impacts, risks, and adaptation in the world. There are a number of assessment products from other countries, each with its own distinct development process, structure, and intended purpose. This appendix is intended to place the Fourth National Climate Assessment (NCA4) within a broader international landscape of assessment activities and to compare it with other approaches.

The approach taken in this appendix has been to select a small set of assessment models from geographically varied nations with diverse capacities to conduct such assessments. Information on the assessment mandates and requirements, process, content structure, and international dimensions are included for each assessment. Because this appendix is intended to be illustrative rather than comprehensive, it does not summarize every report produced internationally—including, for example, the most recent climate assessment produced by the European Union.[1]

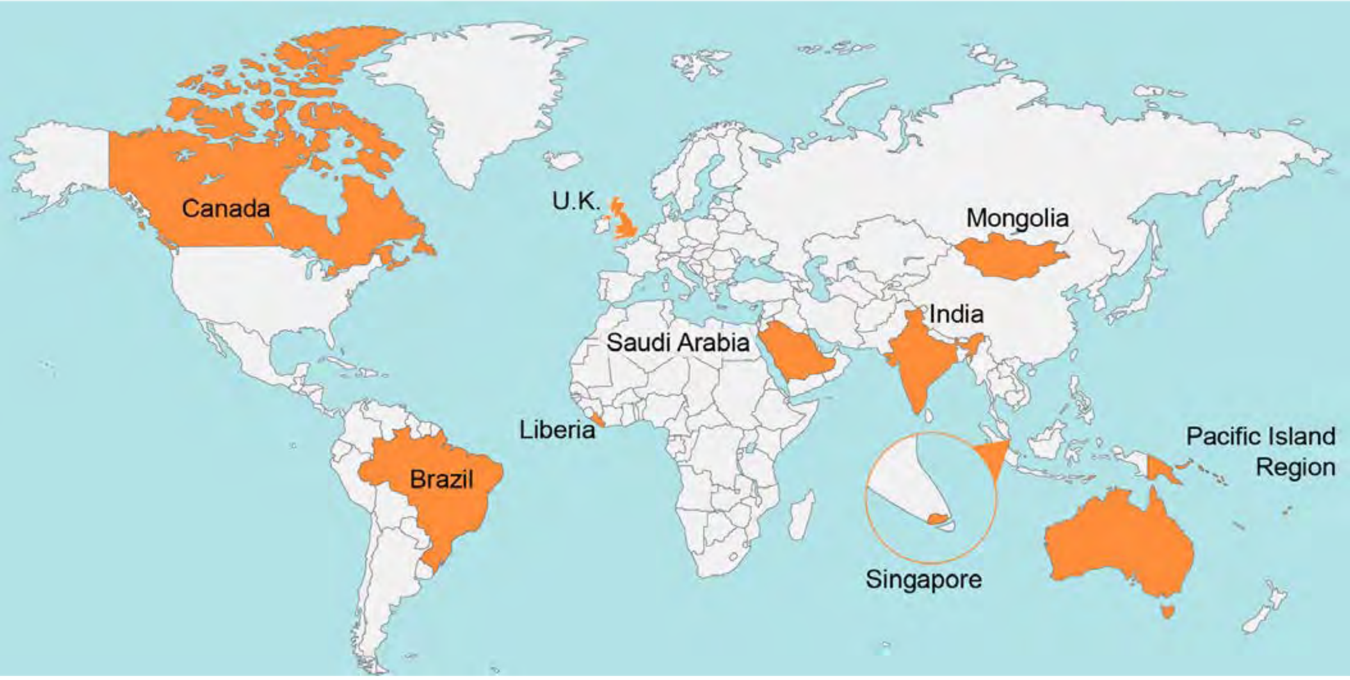
Selected National Climate Assessments

Figure A4.1: The U.S. National Climate Assessment represents one model for conducting national climate assessments, but there are many other national assessment models from countries around the world. Table A4.1 highlights key attributes for each national assessment model chosen for inclusion in this appendix, namely the assessment model type, a link to the assessment website, and the number of assessments to date (and the years they were completed). Source: USGCRP.

This appendix, one of several new additions to the NCA, was made in response to gaps identified in previous NCAs, as well as public input during the NCA4 scoping process—namely, to integrate the international context across NCA4 and, specifically, to include how NCA4 relates to complementary international assessment efforts. Therefore, in addition to this appendix, NCA4 includes a new national-level topic chapter focusing on U.S. international interests (see Ch. 16: International). The Hawaiʻi & U.S.-Affiliated Pacific Islands and (new) U.S. Caribbean regional chapters are intended to provide an entry point for Small Island Developing States (SIDS) to consider similarities in the risks they face and inform adaptation efforts within their own borders. Moreover, numerous case studies embedded throughout the report examine transboundary and international trade and economic issues.

Table A4.1: Summary of Assessment Models by Country

Nation(s)	Assessment Model	Number of Assessments to Date
Brazil	Not mandated by law, developed by a scientific panel established by ministerial ordinance, and modeled after IPCC assessment reports. http://www.pbmc.coppe.ufrj.br/en/	1 assessment (2013)
Canada	Not mandated by law, developed by federal government departments and modeled after the NCA4. http://www.nrcan.gc.ca/environment/impacts-adaptation/10029	6 assessments (1998, 2008 [2], 2014, 2016, 2017)
India	Not mandated by law, developed by domestic research institutions established by ministerial ordinance. http://www.moef.nic.in/division/indian-network-climate-change-assessment	1 assessment (2010)
Liberia	Not mandated by law, developed with U.S. support to fill knowledge gaps resulting from intra-national conflict. https://www.researchgate.net/publication/237102310_liberia_climate_change_assessment	1 assessment (2013)
Mongolia	Not mandated by law, developed by ministerial climate change office. http://www.jcm-mongolia.com/wp-content/uploads/2015/11/MARCC-Final-Bk-2014-book-lst.9.17-ilovepdf-compressed.pdf	2 assessments (2009, 2014)
Pacific Islands	Not mandated by law, developed as a collaborative regional-scale assessment between Australian agencies and Pacific countries. https://www.pacificclimatechangescience.org/publications/reports/	1 assessment (2011)
Saudi Arabia	Not mandated by law, voluntarily developed by national government as part of UNFCCC reporting requirements. http://www.cdmdna.gov.sa/report/40/third-national-communication-of-the-kingdom-of-saudi-arabia	3 assessments (2005, 2011, 2016)
Singapore	Not mandated by law, commissioned by government, and developed by a mixed team of national and international partners. http://ccrs.weather.gov.sg/Publications-Second-National-Climate-Change-Study-Science-Reports/	1 assessment (2015)
United Kingdom	Mandated by law, developed by a statutory independent committee. https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/uk-climate-change-risk-assessment-2017/	2 assessments (2012, 2017)

Federative Republic of Brazil[2,3]

Overview

Brazil released a National Assessment Report on Climate Change (RAN1) in 2013. The report was produced by a national scientific panel established by the government and was modeled on the Assessment Reports produced by the Intergovernmental Panel on Climate Change (IPCC). The RAN1 describes observed and projected impacts, assesses vulnerabilities in different national sectors and regions, and identifies options for adaptation measures. The report is intended to inform the development of the country's national planning activities related to climate change.

Assessment Mandate and Objectives

While Brazil does not have a nationally mandated climate assessment, the government has recognized the need for a national scientific body capable of providing policymakers at the federal, state, and local levels with objective information on the environmental, social, and economic effects of climate change. To this end, the Brazilian Panel on Climate Change (PBMC) was created in 2009 by a joint ordinance of the Ministry of the Environment and the Ministry of Science, Technology, Innovation and Communication.

The structure of the PBMC is based on the IPCC and includes a Steering Committee, Scientific Committee, Executive Secretariat, Working Groups, and Technical Support Units. The Panel is responsible for creating a range of policy-relevant products, including National Assessment Reports that provide a comprehensive scientific assessment of climate changes relevant to Brazil, Special Reports focusing on specific topics, and Technical Reports to help develop methods for monitoring and evaluating Brazil's greenhouse gas emissions. The PBMC represents the first national effort to consolidate and organize existing knowledge on climate change in Brazil onto a single platform. The Panel's report is intended to support the development and implementation of public policies such as the National Plan on Climate Change, Sectoral Mitigation and Adaptation Plans to Climate Change, and the National Adaptation Plan. As of October 2017, the RAN1 was the only national assessment report published by the Panel.

Assessment Process

Under the supervision of the PBMC's Steering Committee, the RAN1 report was written by approximately 100 scientists drawn from national research institutions and distributed across the Panel's three Working Groups (WGs), each of which composed a separate volume for the report. The Panel's Scientific Committee, composed of the coordinators of the WGs, developed the scope of each WG volume, coordinated the drafting of the report, and provided guidance to authors and reviewers throughout the process. The Panel's Steering Committee selected the authors through a public call, approved the Scientific Committee's proposed scoping for the report, approved the various drafts, and provided general direction for the Panel's work. At the end of the process, a Summary for Policy Makers was approved by the PBMC Plenary, which included the Steering and Scientific Committees' memberships, as well as representatives from federal and state governments. In the RAN1, the PBMC made use of the work of a range of observational and modeling research programs that have recently been developed in Brazil at the national and state levels.

Assessment Content Structure

The RAN1 report consists of three separate volumes, each of which is produced by one of the PBMC's three WGs and matches the structure of the IPCC Assessment Reports: Volume 1: The Scientific Basis of Climate Change; Volume 2: Impacts, Vulnerability and Adaptation; Volume 3: Mitigation of Climate

Change. Volume 1 surveys the current state of the scientific knowledge of climate change in Brazil and South America. Volume 2 evaluates the projected climate impacts and vulnerabilities across a range of natural systems, in five national regions (Northern, Northeast, Southern, Southeast, Center-West), and in key societal sectors (Rural and Urban communities, Energy, Industry, and Transportation). A topic receiving special focus is the impact of climate change on human health, well-being, and safety. Each volume was originally drafted in Portuguese but also has an accompanying Executive Summary in English.

International Dimensions

The RAN1 report does not explicitly consider the international dimensions of the impacts of climate change on Brazil. Some findings of the assessment were, however, incorporated into Brazil's 2016 National Communication, which it shared with the international community as part of its United Nations Framework Convention on Climate Change (UNFCCC) reporting requirements. The work of the PBMC is also intended to support international cooperation among developing countries and help countries build their capacity to respond to climate change through the sharing of assessment methodologies, the knowledge gained from these assessments, and Brazil's own national experiences with climate change. This is part of the PBMC's efforts to advance greater South–South dissemination and capacity building. The PBMC also received support from the British Government's Department for International Development.

Canada[4]

Overview

The government of Canada has completed six national-scale science assessments of climate change impacts and adaptation since 1998. Each assessment has included regional and/or sectoral analysis. Led by federal government departments, these assessments involved multiyear, collaborative processes that engaged academia, all levels of government, industry associations, Indigenous organizations, and the private sector. The current assessment process was launched in 2017 and will be completed in 2021.

Assessment Mandate and Objectives

National assessment products, rather than being nationally mandated, are deliverables of government programs supported though specific federal budget cycles. Assessment processes focus on the development and dissemination of products that synthesize and provide value-added analysis of the current state of knowledge. Assessments build awareness of the issues; inform research priorities, policy responses, and adaptation strategies; and enhance capacity to undertake adaptation. These goals are achieved through an inclusive, scientifically rigorous assessment process and the resulting reports.

Assessment Process

The lead federal department (currently, Natural Resources Canada) works with contributing departments to coordinate the assessment process and provide other secretariat functions. A multi-stakeholder advisory committee oversees the process and provides guidance and input throughout, from scoping to post-release. Subject matter experts are engaged as lead and contributing authors, while expertise in areas such as information technology and technical editing is contracted, as required. In addition, each assessment process includes extensive peer review to ensure accuracy and relevance. New elements of the current assessment process include a greater focus on communications, increased engagement of a broad range of Canadians, and the development of a suite of products that will be released over the assessment cycle, rather than just one large volume at the end.

Assessment Content Structure

Canadian assessments focus on climate change impacts and adaptation and draw from all relevant existing sources of knowledge (peer-reviewed publications, gray literature, Indigenous knowledge, and practitioner experience). Climate trends and projections for Canada are included to establish a robust, national overview of current and future changes in physical climate, in the context of informing the impacts and adaptation discussions. Since assessment activities are not legislated, there is flexibility in determining the content and structure, and these decisions take user needs into account. Past assessments have taken either a regional approach—addressing all major regions of Canada or a specific sensitive region (for example, marine coasts)—or a sectoral approach, focusing on a specific sector (for example, health or transportation) or multiple sectors within one volume. Increased engagement, interest, and resources have allowed the current assessment process to expand to include both regional and sectoral volumes, as well as stand-alone reports on climate trends and projections (led by Environment and Climate Change Canada) and on health issues (led by Health Canada).

International Dimensions

The 2008 assessment[5] included a chapter titled "Canada in an International Context." This chapter examined how climate change impacts on other countries, and their adaptation responses, could affect Canada. Sections focused on continental effects (North America), the surrounding oceans, and global impacts. The chapter also discussed Canada's international obligations on adaptation. The 2021 assessment will include a chapter on international dimensions that addresses transboundary issues, trade and supply chains, and linkages between adaptation, sustainable development, and disaster risk reduction globally.

Republic of India[6]

Overview

In 2010, India produced an assessment focused on a combined regional and sectoral analysis of climate change impacts through 2030. While not mandated by law, the federal government called for the assessment to be produced by domestic research institutions. The report represents the nation's first attempt to produce its own comprehensive climate impacts assessment and provides an integrated assessment of four primary regions and four primary sectors of key economic importance to the country. It focuses on observed and projected impacts and potential adaptation measures.

Assessment Mandate and Objectives

While India does not have a nationally mandated climate assessment, the government has stated the need for a comprehensive framework for assessing national- and state-level climate impacts, drawing from domestic technical and policy expertise. In 2009, the Ministry of Environment and Forests established the Indian Network for Climate Change Assessment (INCCA) to conduct research on climate drivers and impacts, prepare assessments of national vulnerability and adaptation, develop decision-support systems, and build capacity for the management of climate risks and opportunities. The broad purpose of the INCCA is to build an independent national research capacity for understanding and responding to climate change and to reduce dependence on external assessments and information sources.

Assessment Process

The INCCA brings together 125 research institutions and more than 250 scientists from across the country. The 2010 assessment report was prepared by 43 researchers from 18 separate institutions, led by the Ministry of Environment and Forests (now the Ministry of Environment, Forest and Climate Change). The Ministry also organized a series of consultative meetings in 2009 and 2010 to inform the report's development. For the analysis of current and projected climate risks, the report utilized both historical observations and high-resolution climate projections using modeling tools obtained from the United Kingdom's Hadley Centre for Climate Prediction and Research.

Assessment Content Structure

The INCCA 2010 report is organized as a "4×4" assessment model that explores the impacts of climate change through the 2030s focused on four key climate-dependent sectors of the Indian economy (Agriculture, Water, Natural Ecosystems and Biodiversity, and Human Health) in four climate-sensitive regions (the Himalayan region, the Western Ghats, the Coastal Area, and the North-East region). The report provides an introduction to the INCCA framework, a discussion of regional climate observations and projections, an assessment of each sector and region, and an assessment of research needs moving forward.

International Dimensions

The INCCA 2010 report does not explicitly consider the international dimensions of the impacts of climate change on India. The findings of the assessment were, however, subsequently updated and incorporated into India's 2012 National Communication, which India shared with the international community through the UNFCCC. The reports were also produced using financial and technical support from international partners.

In January 2015, the United States and India created the Partnership for Climate Resilience. This Partnership aims to strengthen scientific cooperation on climate research and improve information available to decision-makers, building on the 2010 climate change assessment. Experts from the National Oceanic and Atmospheric Administration and academia, with support from the State Department, have partnered with Indian scientific experts and institutions to develop downscaled data for the Indian subcontinent at higher resolution than was previously available and to improve the capacity of local decision-makers to understand, predict, and plan for current and future impacts of climate variability and change.

Republic of Liberia[7]

Overview

In 2013, the U.S. Agency for International Development (USAID) Mission in Liberia commissioned the Republic of Liberia's Climate Change Assessment with involvement from the Liberian government. This international support provided Liberia with additional capacity to advance climate science data to the benefit of Liberian decision-makers. The assessment focused on potential climate change impacts on key Liberian natural resources and used refined downscaled modeling to produce data more targeted to the needs of Liberian decision-makers.

Assessment Mandate and Objectives

In March 2013, the Liberia USAID Mission produced Liberia's Climate Change Assessment to analyze natural resource vulnerabilities with respect to USAID climate change programs in the country. A key motivation for the report was to fill the knowledge gap caused by the loss of climate and environmental information during the country's civil wars. Its objectives were, broadly speaking, twofold: 1) assess the vulnerabilities of natural systems, and 2) provide a knowledge base to promote national climate resilience and improve the condition of rural subsistence farming communities.

Assessment Process

Although this assessment was not nationally mandated or produced by the national government, several Liberian agencies were engaged in developing the assessment in partnership with U.S. federal agencies. It was prepared by the U.S. Department of Agriculture's Forest Service International Programs and reviewed by USAID. To achieve its objectives, the Liberia USAID Mission, in collaboration with the U.S. Forest Service, tasked a multidisciplinary team from the Forest Service Southern Research Station with conducting a climate change assessment. The team briefed Liberian agencies and civil society on the results. It also provided USAID and the Environmental Protection Agency of the Republic of Liberia with the modeled climate data and targeted training on how they might use the data.

Assessment Content Structure

The report focuses on the potential impacts of climate change on agriculture, fisheries, forests, energy, and mining. The assessment also touches on social vulnerability and the capacity of key segments of the Liberian population to adapt to current and projected climate change. It also examines the impacts on society from policy responses to climate change.

International Dimensions

This assessment was launched and largely conducted by an external international entity, namely USAID, though the Liberian government was involved in the process. The climate projections also utilized modeling tools and data obtained from the international community.

Mongolia[8]

Overview

The government of Mongolia has produced two Mongolia Assessment Reports on Climate Change (MARCC), in 2009 and 2014. The assessments are intended to serve as a definitive source of information on the latest research on climate change as it relates to Mongolia. This includes observed and projected climate changes; impacts on environmental, economic, and social sectors; and information on societal responses to climate change. The findings and recommendations of the MARCC reports are intended to feed into the country's national development programs and climate action plans.

Assessment Mandate and Objectives

While there is no explicit legal mandate for the MARCC, it does exist within an evolving national legal and policy framework to address climate challenges and meet Mongolia's obligations under international agreements on the environment and climate change. Under the country's revised Law on Air (2012), the Ministry of Environment and Tourism manages a Climate Change Coordination Office (CCCO), which implements Mongolia's commitments to the UNFCCC and integrates climate change issues into other national sectors. In addition, a National Action Programme on Climate Change (NAPCC), approved by Parliament in 2011, defines strategic objectives and outlines specific activities to integrate climate change concerns into national development plans and action plans. The MARCC 2014 report is intended to support the NAPCC by presenting the most current knowledge of observed and projected climate change. It does so by describing climate impacts on human and natural systems, highlighting strategies and technology needs for mitigation/adaptation measures, presenting a national greenhouse gas (GHG) inventory, and explaining the policy framework for climate action in Mongolia. The report is designed for use by a wide audience: government officials, policy- and decision-makers, members of professional societies and scientific communities, educators and students, and the general public.

Assessment Process

The MARCC 2014 report was prepared under the supervision of the chair of the CCCO, with logistical and technical support from CCCO staff. Financial support for preparation and publication of the report was provided by the German development agency GIZ (German Corporation for International Cooperation) on behalf of the German Federal Ministry for Economic Cooperation and Development. Subject matter experts wrote each chapter. The document was originally drafted in Mongolian and then translated into English. In its presentation of current and projected climate change, MARCC 2014 made use of the IPCC's Fifth Assessment Report (AR5).

Assessment Content Structure

The MARCC 2014 report begins with basic information on observed and projected climate change in Mongolia, organized at the national and regional level. Subsequent chapters organize the impacts of climate change sectorally, on a range of natural and human systems. For natural systems, the report focuses on soil and pasture, forest ecosystems, fauna, water resources, natural disasters, land degradation and desertification, and dust/sand storms. For human systems, the report focuses on animal husbandry, agriculture, poverty and human development, infrastructure, and human health. Later chapters review adaptation options and possible mitigation measures, including a national GHG inventory and related technology issues. The final chapter covers policy frameworks, legal instruments, and institutional arrangements.

International Dimensions

While neither the MARCC 2009 nor the MARCC 2014 explicitly considers the international dimensions of climate change impacts on Mongolia, both reports do provide descriptions of the international policy setting within which Mongolia's climate change efforts exist. In particular, the MARCC 2014 describes in detail Mongolia's recent engagement with a range of international organizations to develop its domestic climate change policy and related interventions, in general. In addition, both the 2009 and 2014 MARCC reports were produced with financial and technical support from international partners.

Pacific Islands[9]

Overview

The Australian government published a Climate Change in the Pacific (CCP) report in 2011. The regional-level report provides a peer-reviewed scientific assessment of how the climate of the western Pacific region is changing. The report was produced through a collaboration between Australian government agencies and Pacific countries. It reviews current trends and projections of climate change for 14 Small Island Developing States (SIDS) and Timor-Leste, and identifies research and knowledge gaps in the region.

Assessment Mandate and Objectives

The significant research gaps identified in the IPCC's Fourth Assessment Report (AR4) served as the foundation for the creation of Australia's Pacific Climate Change Science Program (PCCSP). The objectives of the program are to conduct comprehensive climate change science, build capacity in partner countries across the Pacific to undertake scientific research, and disseminate information to partner countries' stakeholders and other parties. As part of Australia's five-year International Climate Change Adaptation Initiative, the PCCSP produced the Climate Change in the Pacific report in 2011. The report is intended to help countries in the Pacific prioritize adaptation measures, assess their vulnerability, develop adaptation strategies, and address research gaps described in the IPCC's AR4.

Assessment Process

The PCCSP is a collaborative research partnership among Australian government agencies, 14 Pacific Island countries, and Timor-Leste, as well as regional and international organizations. The 14 Pacific countries are the Cook

Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Sāmoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. To ensure that research is of relevance to partner country decision-makers, coordinated information sharing, capacity building, and engagement have been conducted throughout all research areas and among all partner countries.

Assessment Content Structure

This report contains two volumes. The first provides a detailed assessment and analysis of changes in the observed and projected climate of the PCCSP region. The second includes climate change reports for each partner country. Each of the 15 reports includes sections on seasonal cycles, climate variability, observed annual trends, and projections for atmospheric and oceanic variables.

International Dimensions

Climate Change in the Pacific is a regional scientific assessment supported by the government of Australia that involves collaboration with multiple countries, both within the Pacific region and beyond it through the contributions of international organizations.

Kingdom of Saudi Arabia[10]

Overview

The government of the Kingdom of Saudi Arabia (KSA) has voluntarily produced three assessments of the nation's vulnerability to climate change. The most recent national vulnerability assessment was completed in 2016 and incorporated into the National Communication submitted by the KSA to satisfy its UNFCCC reporting requirements. The vulnerability assessments identify current and future climate-related impacts as well as potential adaptation measures in specific sectors. They also identify knowledge gaps to be addressed by future assessments.

Assessment Mandate and Objectives

While the KSA does not have a nationally mandated climate assessment, it is required, as part of its reporting obligations and commitments under the UNFCCC (Article 12 and subsequent decisions taken at Conferences of the Parties), to submit National Communications that provide certain information related to its greenhouse gas (GHG) emissions and the implementation of actions to address climate change. These reports provide the international community with a recent inventory of each Party's GHG emissions, a description of the policy initiatives that the country has taken to respond to and prepare for climate change, and any other information relevant to the implementation of its commitments under the UNFCCC. As part of this reporting, the KSA has included a national climate assessment in all of its National Communications, submitted in 2005, 2011, and 2016. These assessments analyze regional climate trends and projections and their impacts on a range of nationally important sectors.

Assessment Process

The KSA's most recent National Communication was produced by a Designated National Authority, in coordination with a team of academics, consultants, and other experts drawn from relevant government ministries, research institutions, and other organizations. In particular, the General Authority of Meteorology and Environmental Protection (the Kingdom's environmental agency) and the Ministry of Energy, Industry and Mineral Resources played important roles in its development. The report was produced with assistance from the national oil and gas company (Saudi Aramco), the United Nations Environment Programme, and the Global Environment Facility. For the analysis of current and projected climate risks, the report utilized historical observations and high-resolution climate projections using modeling tools obtained from the United

Kingdom's Hadley Centre for Climate Prediction and Research.

Assessment Content Structure

Within the KSA's Third National Communication, the climate assessment component includes a chapter focusing on climate science, describing baseline conditions, recent trends, and future climate scenarios, as well as the methodologies employed and climate model outputs. Subsequent sectoral chapters describe vulnerabilities and identify national adaptation measures covering the areas of water resources, desertification, agriculture and food security, and human health. Each of these chapters offers more detailed and technical discussion of the sectoral impacts as well as recommendations for future research to address information and data gaps.

International Dimensions

The KSA's National Communications have not explicitly considered the international dimensions of climate change impacts on the country. The reports reflect the country's ongoing engagement with the UNFCCC process for assessing climate-related risks and developing policies to address them. The reports were also produced using financial and technical support from international partners.

Republic of Singapore[11]

Overview

The Republic of Singapore's National Climate Change Studies are voluntary reports, commissioned by the government and produced by a mixed team of national and international partners. Singapore has undertaken two studies, the first of which was completed in 2015 and the second of which is currently underway and will include a vulnerability analysis.

Assessment Mandate and Objectives

The National Environment Agency of Singapore (NEA) commissioned the current National Climate Change Study in recognition of the island nation's increasing vulnerability to climate change. The purpose is to assess the current and projected impacts from climate change, focusing on variables of greatest importance to the country (temperature, precipitation, and sea level), and to assess the vulnerability of various sectors to a changing climate. The results of the study will feed into the next stage of Singapore's national adaptation planning efforts.

Assessment Process

The NEA leads the development of the study, which is divided into two phases. Phase 1, which was published in 2015, provided long-term climate projections, while Phase 2, currently under development, will assess the vulnerability of Singapore's population, environment, and infrastructure to a changing climate. The work on Phase 1 was performed jointly by experts from the Centre for Climate Research Singapore and the Met Office Hadley Centre in the United Kingdom, with contributions from partners at the Australian Commonwealth Scientific and Industrial Research Organisation and the United Kingdom's National Oceanography Centre–Liverpool. The focus of the Phase 1 study was to produce high-resolution regional climate and sea level projections that extend to 2100. To ensure that outcomes from the study would be of use to decision-makers, stakeholder engagement was integrated early on in the process, with representatives from a range of national agencies taking part. In particular, engagement activities involved stakeholders' focusing on six thematic clusters: coastal protection; water resources and drainage; public health; network infrastructure; building, structure, and town infrastructure; and biodiversity and greenery.

Assessment Content Structure

The Phase 1 report of Singapore's Second National Climate Change Study is made up of 10 primary chapters, each focusing on a specific element of the modeling process that generated the high-resolution projections to be used in the vulnerability assessment. The report also includes detailed technical appendices and supplementary information.

International Dimensions

Phase 1 of the current study was completed in close partnership with the United Kingdom and Australia. Additionally, the foundation for its scientific assessment stemmed from work conducted by the IPCC. The completed study will not explicitly consider international effects.

United Kingdom[12]

Overview

The government of the United Kingdom (UK) is legally required to produce a Climate Change Risk Assessment (CCRA) every five years and then develop National Adaptation Programmes to address those risks and build resilience to climate change. The core component of the CCRA is an independently produced Evidence Report that assesses climate risks and impacts in the UK. The Evidence Report feeds into a high-level Synthesis Report that identifies key areas of climate risk to be prioritized for action. The government evaluates this Synthesis Report and produces its final Risk Assessment, which is presented to Parliament. The most recent Evidence Report was developed using a risk-based framing and explicitly considers the international dimensions of climate impacts to the UK.

Assessment Mandate and Objectives

The 2008 Climate Change Act requires the UK government to present a CCRA to Parliament every five years. The purpose of the assessment is to evaluate the risks that current and predicted climate change impacts pose to the UK and, ultimately, to guide the development of National Adaptation Programmes for the UK and its component countries (the administrations of England, Northern Ireland, Scotland, and Wales).

Assessment Process

Under the 2008 Climate Change Act, two CCRAs have been completed, one in 2012 and the most recent in 2017. The Act establishes an independent body, the Committee on Climate Change, whose Adaptation Sub-Committee (ASC) was responsible for the CCRA Evidence Report and Synthesis Report in 2017. The Evidence Report summarizes the current state of knowledge of climate risks and opportunities in the UK and identifies priority areas needing urgent further action over the next five years. For the most recent Evidence Report, the ASC convened teams of experts to assess a wide range of climate risks and opportunities and assign urgency scores to inform national adaptation planning. The analysis was supplemented by several specially commissioned research studies on specific climate impacts and was informed by engagement with and review by stakeholders inside and outside of the government and across all four UK countries. The Synthesis Report, authored by the ASC, summarizes the Evidence Report and then identifies six areas of risk to be managed as priorities for the next five years. For the most recent CCRA, the government largely approved the conclusions from the various products of the ASC, which it produced in its final UK Climate Change Risk Assessment 2017.

Assessment Content Structure

The most recent Evidence Report includes multiple individual products. The main report is an independent analysis authored by academics, consultants, and other experts in the public and private sectors, as well as civil society organizations throughout the UK. It reviews evidence for current and future climate change in the UK, provides a description of the assessment methodology, and includes technical chapters focused on specific sectors. Separate national summaries, authored by the ASC, present evidence specific to Scotland, England, Northern Ireland, and Wales.

International Dimensions

The CCRA Evidence Report has expanded since its inception to examine impacts at increasingly wider scales, both across sectors and geographically. While the focus of the first report was on a limited set of direct impacts within the UK, the most recent CCRA also considers the impacts on the UK from international effects, both direct (for example, through disruption of trade and supply chains) and indirect (for example, through price volatility of imported commodities). These topics are explored in a dedicated international dimensions chapter.

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A5 Appendix 5. Frequently Asked Questions

This appendix is an update to the frequently asked questions (FAQs) presented in the Third National Climate Assessment (NCA3). New questions based on areas of emerging scientific inquiry are included alongside updated responses to the FAQs from NCA3. The answers are based on the U.S. Global Change Research Program's (USGCRP) sustained assessment products, other peer-reviewed literature, and consultation with experts.

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Contents

Introduction to Climate Change

How do we know Earth is warming?

Many indicators show conclusively that Earth has warmed since the 19th century. In addition to warming shown in the observational record of oceanic and atmospheric temperature, other evidence includes melting glaciers and continental ice sheets, rising global sea level, a longer frost-free season, changes in temperature extremes, and increases in atmospheric humidity, all consistent with long-term warming.

Observations of surface temperature taken over Earth's land and ocean surfaces since the 19th century show a clear warming trend. Temperature observations have been taken consistently since the 1880s or earlier at thousands of observing sites around the world. Additionally, instruments on ships, buoys, and floats together provide a more-than-100-year record of sea surface temperature showing that the top 6,500 feet of Earth's ocean is warming in all basins.[1] These observations are consistent with readings from satellite instruments that measure atmospheric and sea surface temperatures from space. Used together, land-, ocean-, and space-based temperature observations show clear evidence of warming at Earth's surface over climatological timescales (http://www.globalchange.gov/browse/indicators for more indicators of change) (see also Ch. 2: Climate).

Scientists around the world have been measuring the extent and volume of ice contained in the same glaciers every few years since 1980. These measurements show that, globally, there is a large net volume loss in glacial ice since the 1980s. However, the rate of the ice loss varies by region, and in some cases yearly glacier advances are observed (see FAQ "How does climate change affect mountain glaciers?"). Ice sheets on Antarctica and Greenland have been losing ice mass consistently since 2002, when advanced satellite measurements of their continental ice mass began (see FAQ "Is Antarctica losing ice? What about Greenland?"). Arctic sea ice coverage has been monitored using satellite imagery since the late 1970s, showing consistent and large declines in September, the time of year when the minimum coverage occurs.[2]

There are additional observational lines of evidence for warming. For example, the area of land in the Northern Hemisphere covered by snow each spring is now smaller on average than it was in the 1960s.[3] Tide gauges and satellites show that global sea level is rising, both as a result of the addition of water to the ocean from melting glaciers and from the expansion of seawater as it warms (Ch. 2: Climate; Ch. 8: Coastal). Lastly, as air warms, its capacity to hold water vapor increases, and measurements show that atmospheric humidity is increasing around the globe, consistent with a warming climate (see Ch. 3: Water; see also Ch. 1: Overview, Figure 1.2 for more indicators of a warming world).

What makes recent climate change different from warming in the past?

Increases in global temperature since the 1950s are unusual for two reasons. First, current changes are primarily the result of human activities rather than natural physical processes. Second, temperature changes are occurring much faster than they did in the past.

Our planet's climate has changed before. Sedimentary rocks and fossils show clear evidence for a series of long cold periods—called ice ages—followed by warm periods. Common archaeological and geological processes for dating past events show that these cycles of cooling and warming occurred about once every 100,000 years for at least the last million years.

Before major land-use changes and industrialization, changes in global temperature were caused by natural factors, including regular changes in Earth's orbit around the sun, volcanic eruptions, and changes in energy from the sun.[4] Major warming and cooling events were driven by natural variations of Earth's orbit that altered the amount of sunlight reaching Earth's Arctic and Antarctic regions, resulting in the retreat and advance of massive ice sheets. Additionally, quiescent or active periods of volcanic eruptions also could contribute to warming or cooling events, respectively.[5]

Natural factors are still affecting the planet's climate today (see Figure A5.5). Yet since the beginning of the Industrial Revolution, human use of coal, oil, and gas has rapidly changed the composition of the atmosphere (Figure A5.1). Land-use changes (such as deforestation), cement production, and animal production for food have also contributed to the increase in levels of greenhouse gases in the atmosphere. Unlike past changes in climate, today's warming is driven primarily by human activity rather than by natural physical processes (see Figure A5.5) (see also Ch. 2: Climate).

Current warming is also happening much faster than it did in the past. Scientific records from ice cores, tree rings, soil boreholes, and other "natural thermometers"—often called proxy climate data—show that the recent increase in temperature is unusually rapid compared to past changes (see Figures A5.2 and A5.4). After an ice age, Earth typically took thousands of years to warm up again; the observed rate of warming over the last 50 years is about eight times faster than the average rate of warming from a glacial maximum to a warm interglacial period.[4]

Carbon Emissions in the Industrial Age

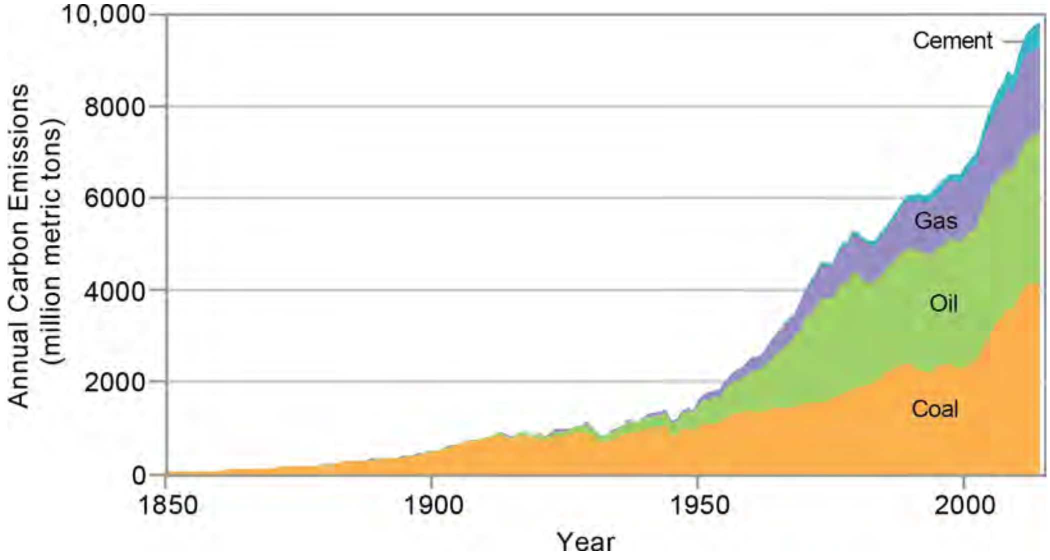


Figure A5.1 Humans have changed the atmosphere by burning coal, oil, and gas for energy and by producing cement. This graph shows the total global carbon emissions from these activities from 1850 to 2009. A range of other human activities, such as cutting down forests and livestock production, account for additional carbon emissions. Source: Walsh et al. 2014.[6]

1,700 Years of Global Temperature Change

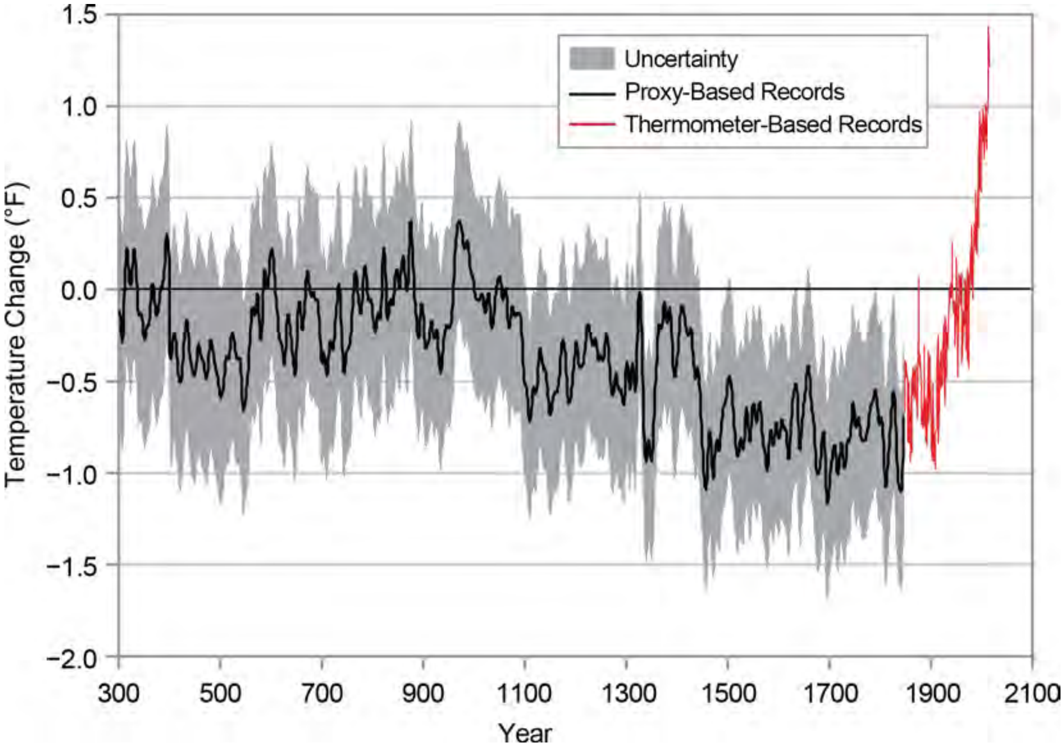


Figure A5.2 Average global temperature has increased rapidly over the last 1,700 years compared to the 1961–1990 average. The red line shows temperature data based on surface observations. The black line shows temperature data from proxies, including data from tree rings, ice cores, corals, and marine sediments. The comparison of proxy- and thermometer-based records suggests that temperatures are now higher than they have been in at least 1,700 years. The steep portion of the graph since about 1950 shows how rapidly temperature has increased compared to previous changes. Source: adapted from Mann et al. 2008.[7]

What’s the difference between global warming and climate change?

Though some people use the terms “global warming” and “climate change” interchangeably, their meanings are slightly different. Global warming refers only to Earth's rising surface temperature, while climate change includes temperature changes and a multitude of effects that result from warming, including melting glaciers, increased humidity, heavier rainstorms, and changes in the patterns of some climate-related extreme events.

By itself, the phrase global warming refers to increases in Earth’s annual average surface temperature. Today, however, when people use the phrase, they usually mean the recent warming that is due in large part to the rapid increase of greenhouse gases (GHGs) in the atmosphere from human activities such as deforestation and the burning of fossil fuels for energy. Thus, “global warming” has become a form of shorthand for a complex scientific process.

The entire globe is not warming uniformly. Some areas may cool (such as the North Atlantic Ocean), while some may warm faster than the global average (such as the Arctic). The term climate change refers to the full range of consequences or impacts that occur as atmospheric levels of GHGs rise and different parts of the earth system respond to a higher average surface temperature. For instance, observed long-term trends, such as increases in the frequency of drought and heavy precipitation events, are not technically warming trends, but they are related to current warming and are processes of climate change (Ch 2: Climate).

Climate Science

What are greenhouse gases, and what is the greenhouse effect?

Greenhouse gases (GHGs) are gases that absorb and emit thermal (heat) infrared radiation. Carbon dioxide, methane, nitrous oxide, ozone, and water vapor are the most prevalent GHGs in Earth's atmosphere. These gases absorb heat emitted by Earth's surface and re-emit that heat into Earth's atmosphere, making it much warmer than it would be otherwise—a process known as the greenhouse effect.

Most of Earth's atmosphere is made up of nitrogen (N_2) and oxygen (O_2), neither of which is considered a greenhouse gas. Other gases, known as greenhouse gases (GHGs), behave very differently from O_2 and N_2 when it comes to infrared radiation emitted from Earth. GHGs, such as water vapor, carbon dioxide (CO_2), and methane (CH_4), have a more complex molecular structure (made up of three or more atoms, as opposed to the symmetrical, two-atom molecules of O_2 and N_2) that absorbs some of the energy emitted from Earth's surface and then re-radiates that energy in all directions, including back down towards the surface. This ultimately traps energy in the lower atmosphere in the form of heat (Figure A5.3). This greenhouse effect makes the average temperature of Earth nearly 60°F warmer than it would be in the absence of these GHGs. Even a tiny amount of these gases can have a huge effect on the amount of heat trapped in the lower atmosphere, just like a tiny amount of anthrax can have a huge effect on human health.

Many GHGs, including CO_2, CH_4, water vapor, and nitrous oxide (N_2O), occur naturally in the atmosphere. However, atmospheric concentrations of these GHGs have been rising over the last few centuries as a result of human activities. In addition, human activities have added new, entirely human-made GHGs to the atmosphere, including chlorofluorocarbons(CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).[5]

As the global population has increased, so have GHG emissions. This in turn makes the greenhouse effect stronger, resulting in higher average temperature around the globe (Ch 2: Climate).

The Greenhouse Effect

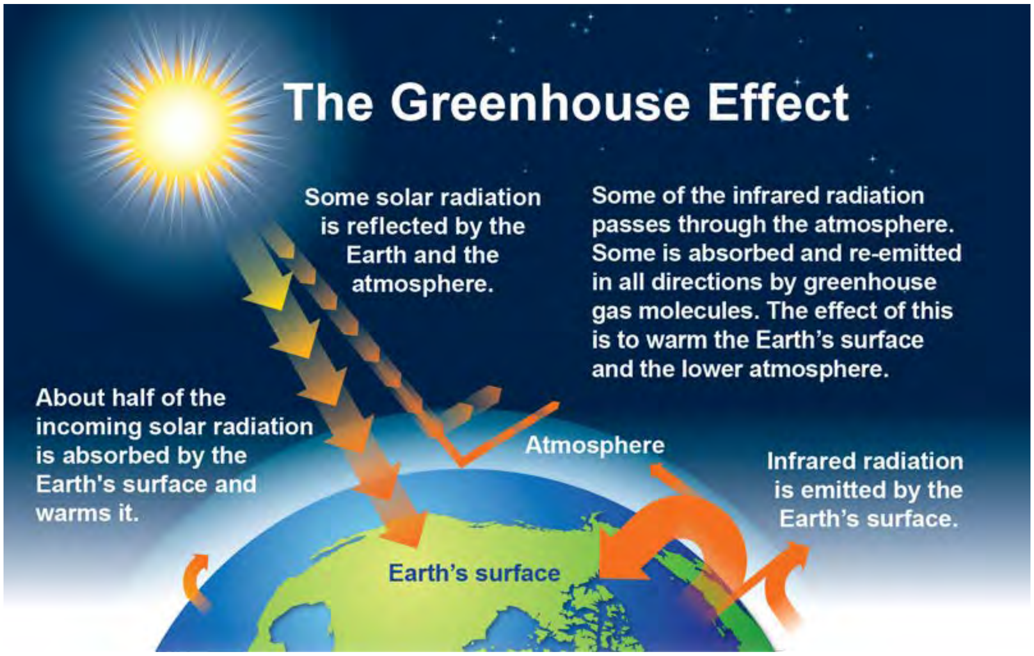


Figure A5.3: The figure shows a simplified representation of the greenhouse effect. About half of the sun's radiation reaches Earth's surface, while the rest is reflected back to space or absorbed by the atmosphere. Naturally occurring greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), do not absorb most of the incoming shortwave (visible) energy from the sun, but they do absorb the longwave (infrared) energy re-radiated from Earth's surface. This energy is then re-emitted in all directions, keeping the surface of the planet much warmer than it would be otherwise. Human activities—predominantly the burning of fossil fuels (coal, oil, and gas)—are increasing levels of CO_2 and other GHGs in the atmosphere, which is amplifying the natural greenhouse effect and thus increasing Earth's temperature. Source: adapted from EPA 2016.[8]

Why are scientists confident that human activities are the primary cause of recent climate change?

Many independent lines of evidence support the finding that human activities are the dominant cause of recent (since 1950) climate change. These lines of evidence include changes seen in the observational records that are consistent with our understanding, based on physics, of how the climate system should change due to human influences. Other evidence comes from climate modeling studies that closely reproduce the observed temperature record.

The Climate Science Special Report[9] concludes, "human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century." The Earth's climate only warms or cools significantly in response to changes that affect the balance of incoming and outgoing energy. Over long timescales (tens to hundreds of thousands of years), orbital cycles produce long periods of warming and cooling. Over shorter timescales, two factors could generally force changes in Earth's temperature to a measurable degree: (1) changes in the amount of energy put out by the sun, and (2) changes in the concentrations of greenhouse gases (GHGs) in Earth's atmosphere. Recent measurements of the sun's energy show no trend over the last 50 years. Additionally, observations show that the lower atmosphere (troposphere) has warmed while the upper atmosphere (stratosphere) has cooled. If the observed warming had been due to an increase in energy from the sun, then all layers of Earth's atmosphere would have warmed, which is not what scientists observe. Thus, we can eliminate changes in the energy received from the sun as a major factor in the warming observed since about 1950.[10]

This leaves the possibility that changes in GHG concentrations in the atmosphere are the primary cause of recent warming. Atmospheric carbon dioxide (CO_2) levels have increased from approximately 270 parts per million (ppm) during preindustrial times to the current 408 ppm observed in 2018 (see https://www.esrl.noaa.gov/gmd/ccgg/trends/)—levels that exceed any observed over the past 800,000 years (Figure A5.4). In addition, atmospheric concentrations of other GHGs (including methane and nitrous oxide) have increased over the same period. This increase in GHG concentrations has coincided with the observed increase in global temperature. Scientists use methods that provide chemical "fingerprints" of the source of these increased emissions and have shown that the 40% increase in atmospheric CO_2 levels since the Industrial Revolution is due mainly to human activities (primarily the combustion of fossil fuels) and not due to natural carbon cycle processes.[5]

Other evidence attributing human activities as the dominant driver of observed warming comes from climate modeling studies. Computer simulations of Earth's climate based on historical data of observed changes in natural and human influences accurately reproduce the observed temperature record over the last 120 years. These results show that without human influences, such as the observed increases in GHG emissions, Earth's surface would have cooled slightly over the past half century. The only way to closely replicate the observed warming is to include both natural and human forcing changes in climate models (Figure A5.5). Thus, the observational record and modeling studies both point to human factors being the main cause for the recent warming (Ch.2: Climate).

800,000 Years of CO_2 and Temperature Change

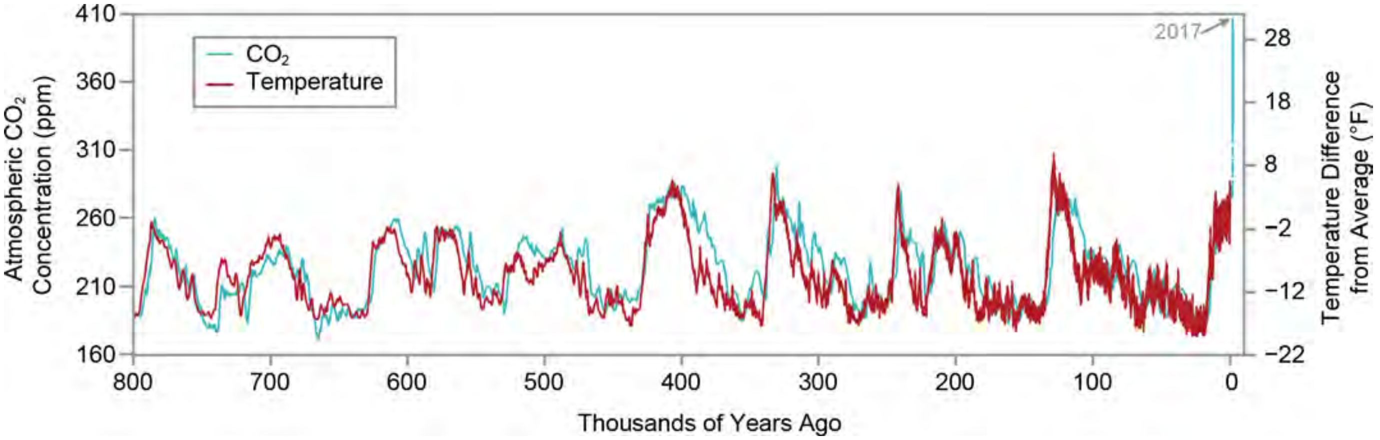


Figure A5.4: This chart shows atmospheric CO_2 concentrations (left axis, blue line) and changes in temperature (compared to the average over the last 1,000 years; right axis, red line) over the past 800,000 years, as recorded in ice cores from Antarctica. Also shown are modern instrumental measurements of CO_2 concentrations through 2017. Current CO_2 concentrations are much higher than any levels observed over the past 800,000 years. Source: adapted from EPA 2017.[11]

Human and Natural Influences on Global Temperature

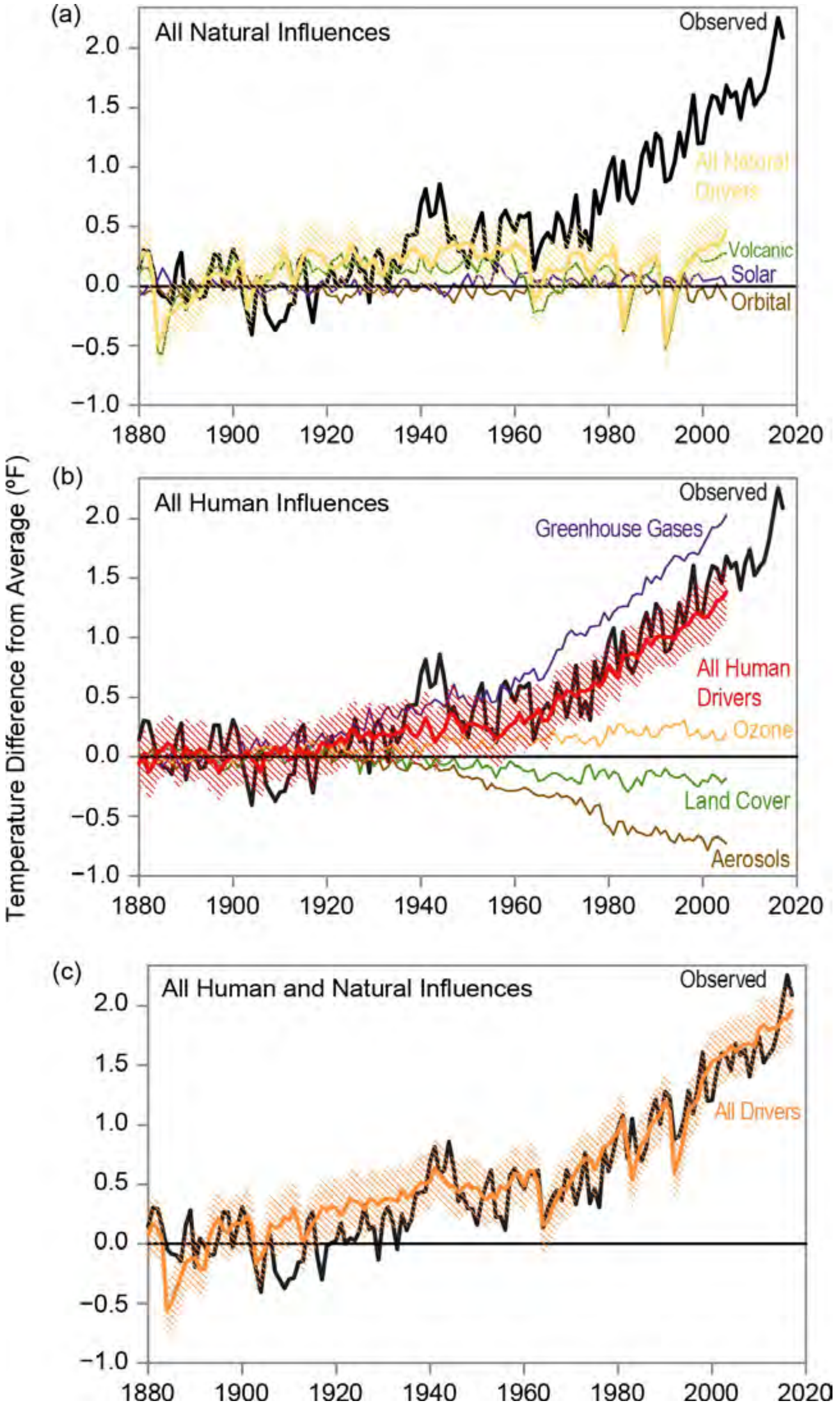


Figure A5.5: Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

Sophisticated computer models of Earth's climate system allow scientists to explore the effects of both natural and human factors. In all three panels of this figure, the black line shows the observed annual average global surface temperature for 1880–2017 as a difference from the average value for 1880–1910.

The top panel (a) shows the temperature changes simulated by a climate model when only natural factors (yellow line) are considered. The other lines show the individual contributions to the overall effect from observed changes in Earth's orbit (brown line), the amount of incoming energy from the sun (purple line), and changes in emissions from volcanic eruptions (green line). Note that no long-term trend in globally averaged surface temperature over this time period would be expected from natural factors alone.[4]

The middle panel (b) shows the simulated changes in global temperature when considering only human influences (dark red line), including the contributions from emissions of greenhouse gases (purple line) and small particles (referred to as aerosols, brown line) as well as changes in ozone levels (orange line) and changes in land cover, including deforestation (green line). Changes in aerosols and land cover have had a net cooling effect in recent decades, while changes in near-surface ozone levels have had a small warming effect.[5] These smaller effects are dominated by the large warming influence of greenhouse gases such as carbon dioxide and methane. Note that the net effect of human factors (dark red line) explains most of the long-term warming trend.

The bottom panel (c) shows the temperature change (orange line) simulated by a climate model when both human and natural influences are included. The result matches the observed temperature record closely, particularly since 1950, making the dominant role of human drivers plainly visible.

Researchers do not expect climate models to exactly reproduce the specific timing of actual weather events or short-term climate variations, but they do expect the models to capture how the whole climate system behaves over long periods of time. The simulated temperature lines represent the average values from a large number of simulation runs. The orange hatching represents uncertainty bands based on those simulations. For any given year, 95% of the simulations will lie inside the orange bands. See Chapter 2: Climate for more information. Source: NASA GISS.

What role does water vapor play in climate change?

Water vapor is the most abundant greenhouse gas (GHG) in the atmosphere and plays an important role in Earth's climate, significantly increasing Earth's temperature. However, unlike other GHGs, water vapor can condense and precipitate, so water vapor has a short life span in the atmosphere. Air temperature, and not emissions, controls the amount of water vapor in the lower atmosphere. For this reason, water vapor is considered a feedback agent and not a driver of climate change.

Water vapor is the primary GHG in the atmosphere, and its contribution to Earth's greenhouse effect is about two or three times that of carbon dioxide (CO_2). Human activities directly add water vapor to the atmosphere primarily through increasing evaporation from irrigation, power plant cooling, and combustion of fossil fuels. Other GHGs, such as CO_2, are not condensable at atmospheric temperatures and pressures, so they will continue to build up in the atmosphere as long as their emissions continue.[12]

The amount of water vapor in the lower atmosphere (troposphere) is mainly controlled by the air temperature and proximity to a water source, such as an ocean or large lake, rather than by emissions from human activities. Fluctuations in air temperature change the amount of water vapor that the air can hold, with warmer air capable of holding more moisture. Increases in water vapor levels in the lower atmosphere are considered a "positive feedback" (or self-reinforcing cycle) in the climate system. As increasing concentrations of other GHGs (for example, carbon dioxide, methane, and nitrous oxide) warm the atmosphere, atmospheric water vapor concentrations increase, thereby amplifying the warming effect (Figure A5.6). If atmospheric concentrations of CO_2 and other GHGs decreased, air temperature would drop, decreasing the ability of the atmosphere to hold water vapor, further decreasing temperature.[5,12]

Water Vapor and the Greenhouse Effect

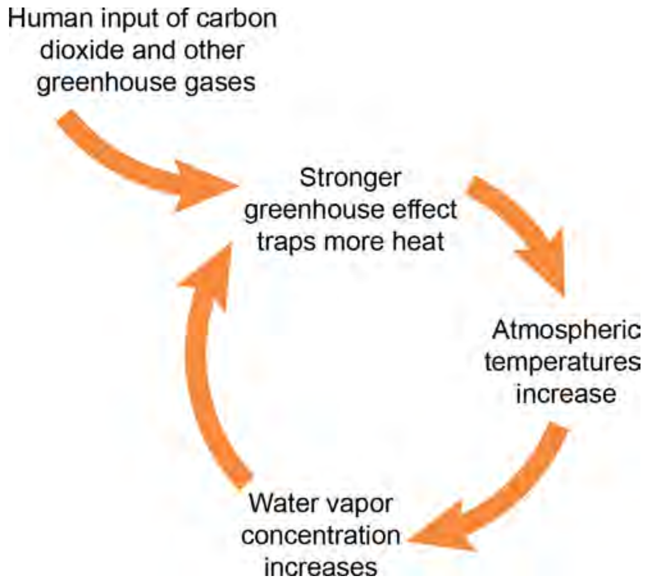


Figure A5.6: As emissions of carbon dioxide and other greenhouse gases increase, the strength of the greenhouse effect increases, which drives an increase in global temperature. This in turn increases the amount of water vapor in the lower atmosphere. Because water vapor is itself a greenhouse gas, the increase in atmospheric water vapor can further strengthen the greenhouse effect. Source: USGCRP.

How are El Niño and climate variability related to climate change?

El Niño and other forms of natural climate variability are not caused by humans, but their frequency, duration, extent, or intensity might be affected by greenhouse gas emissions from human activities. Natural climate variability produces short-term regional changes in temperature and weather patterns, whereas human-caused climate change is a persistent, long-term phenomenon.

Climate variability refers to the natural changes in climate that fall within the observed range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño–Southern Oscillation (ENSO) and other phenomena. ENSO is a quasi-periodic warming or cooling of the of the sea surface temperatures in the tropical eastern Pacific and is often referred to by its phase of El Niño (warm phase) or La Niña (cool phase). These different ENSO phases can have varying ecosystem and economic effects, especially in certain fishing communities, while also influencing weather worldwide (Figure A5.7). In the United States, El Niño conditions generally correspond with warmer than average sea surface and air temperatures along the West Coast, wetter conditions in the Southwest, cooler temperatures in the Southeast, and warmer conditions in the Northeast. In contrast, the La Niña phase of ENSO corresponds to cooler temperature in the U.S. Northwest and dryer and warmer conditions in the Southeast, along with increased upwelling along the West Coast.

Evidence from paleoclimate records suggests that there have been changes in the frequency and intensity of ENSO events in the past. Human-caused climate change might also affect the frequency and magnitude of ENSO events and can exacerbate or ameliorate regional ENSO impacts. For example, if there is a strong La Niña event that results in dry conditions in the Southwest, those conditions may be exacerbated by additional drying due to climate change. ENSO is a complex phenomenon, but new research is shedding light on the many factors influencing how climate change affects the ENSO cycle.[13]

El Niño/La Niña Cause Short-Term Changes in Weather Patterns

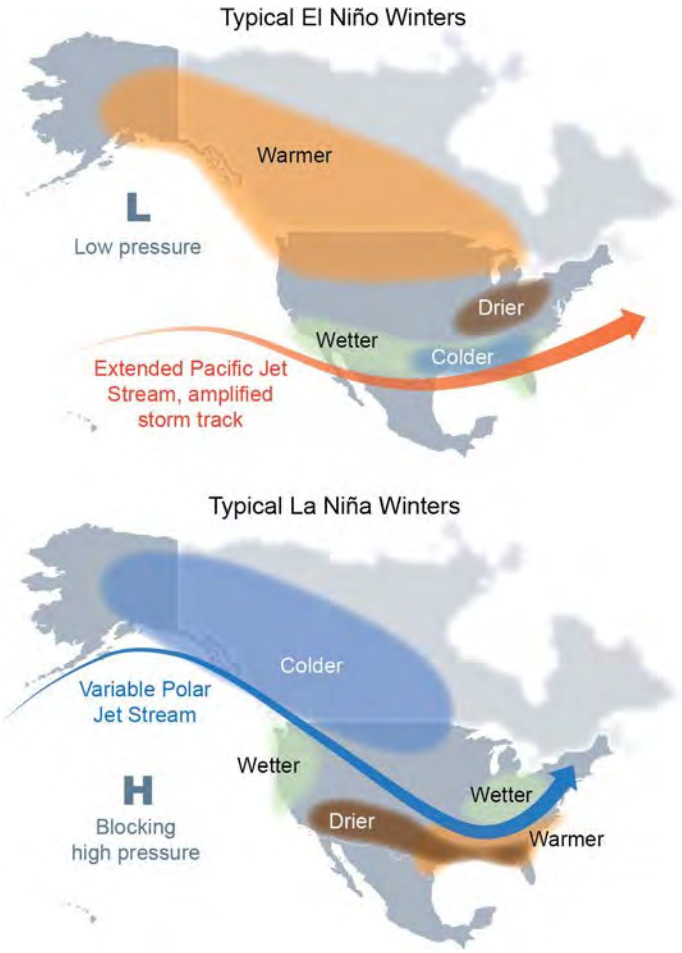


Figure A5.7: El Niño and La Niña events create different weather patterns during winters (January through March) over North America. (top) During an El Niño, there is a tendency for a strong jet stream and storm track across the southern part of the United States. The southern tier of Alaska and the U.S. Pacific Northwest tend to be warmer than average, whereas the southern United States tends to be cooler and wetter than average. (bottom) During a La Niña, there is a tendency for very wave-like jet stream flow over the United States and Canada, with colder and stormier than average conditions across the North and warmer and less stormy conditions across the South. Source: Perlwitz et al. 2017.[13]

Temperature and Climate Projections

What methods are used to record global surface temperatures and measure changes in climate?

Global surface temperatures are measured by using data from weather stations over land and by ships and buoys over the ocean. Global surface temperature records date back more than 300 years in some locations, and near-global coverage has existed since the late 1800s. Multiple research groups have examined U.S. and global temperature records in great detail, taking into account changes in instruments, the time of observations, station location, and any other potential sources of error. Although there are slight differences among datasets—due to choices in data selection, analysis, and averaging techniques—these differences do not change the clear result that global surface temperature is rising.

Climate change is best measured by assessing trends over long periods of time (generally greater than 30 years), which means we need global surface temperature records that include data from before the satellite age. Scientists who obtain, digitize, and collate long-term temperature records take great care to ensure that any potentially skewed measurements—such as a change in instrument method or location or a change in the time of day a recording is made—do not affect the integrity of the dataset. Researchers rigorously examine the data to identify and adjust for any such effects before using it to evaluate long-term climate trends. Different choices in data selection, analysis, and averaging techniques by multiple independent research teams mean that each dataset varies slightly. Even with these variations, however, multiple independently produced results are in very good agreement at both global and regional scales: all global surface temperature datasets indicate that the vast majority of Earth's surface has warmed since 1901 (Figure A5.8).

Scientists also consider other influences that could impact temperature records, such as whether data from thermometers located in cities are skewed by the urban heat island effect, where heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside. When determining climate trends, data corrections to these temperature records have adequately accounted for this effect. At the global scale, evidence of global warming over the past 50 years is still observed even if all of the urban stations are removed from the global temperature record. Studies have also shown that the warming trends of rural and urban areas that are in close proximity essentially match, even though the urban areas may have higher temperatures overall.[14]

Global Temperature Increase Shown in Multiple Datasets

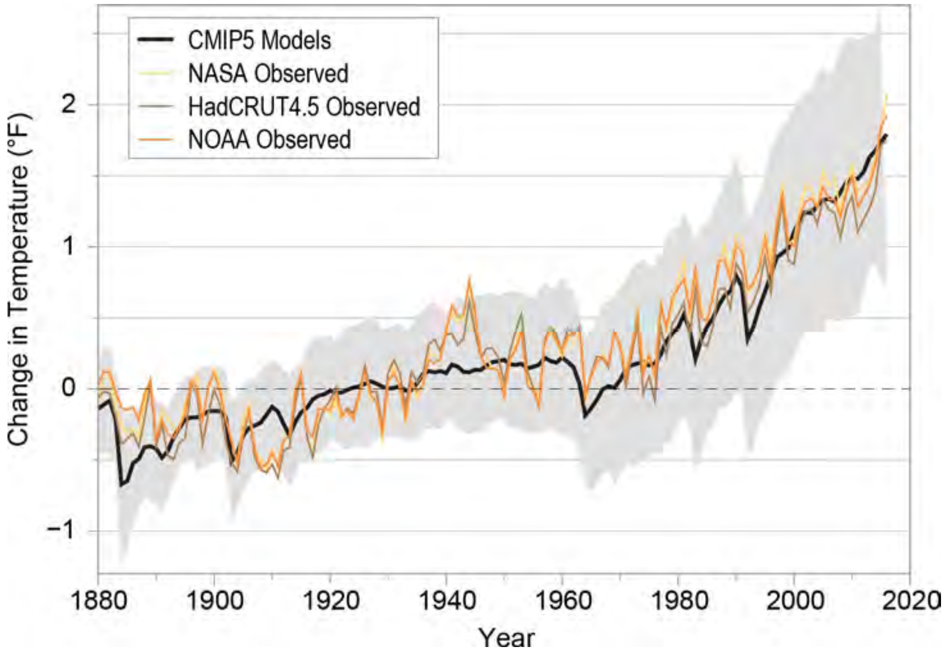


Figure A5.8: This chart shows observations of global annual average temperatures from three different datasets—one from NASA (yellow line), one from NOAA (orange line), and one from the University of East Anglia in conjunction with the United Kingdom's Met Office (HadCRUT4.5, brown line)—along with historical simulations of global temperature from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble of climate models (black line). The lines show annual differences in temperature relative to the 1901–1960 average. Small differences among datasets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. Source: adapted from Knutson et al. 2016.[15]

Were there predictions of global cooling in the 1970s?

No. A review of the scientific literature from the 1970s shows that the broad climate science community did not predict “global cooling” or an “imminent” ice age. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Scientific understanding of what are called the Milankovitch cycles (cyclical changes in Earth’s orbit that can explain the onset and ending of ice ages) led a few scientists in the 1970s to contemplate that the current warm interglacial period might be ending soon, leading to a new ice age over the next few centuries. These few speculations were picked up and amplified by the media. But at that time there were far more scientific articles describing how warming would occur from the increase in atmospheric concentrations of greenhouse gases from human activities, including the burning of fossil fuels (Figure A5.9). The latest information suggests that if Earth’s climate was being controlled primarily by natural factors, the next cooling cycle would begin sometime in the next 1,500 years. However, humans have so altered the composition of the atmosphere that the next ice age has likely now been delayed. That delay could potentially be tens of thousands of years.[6]

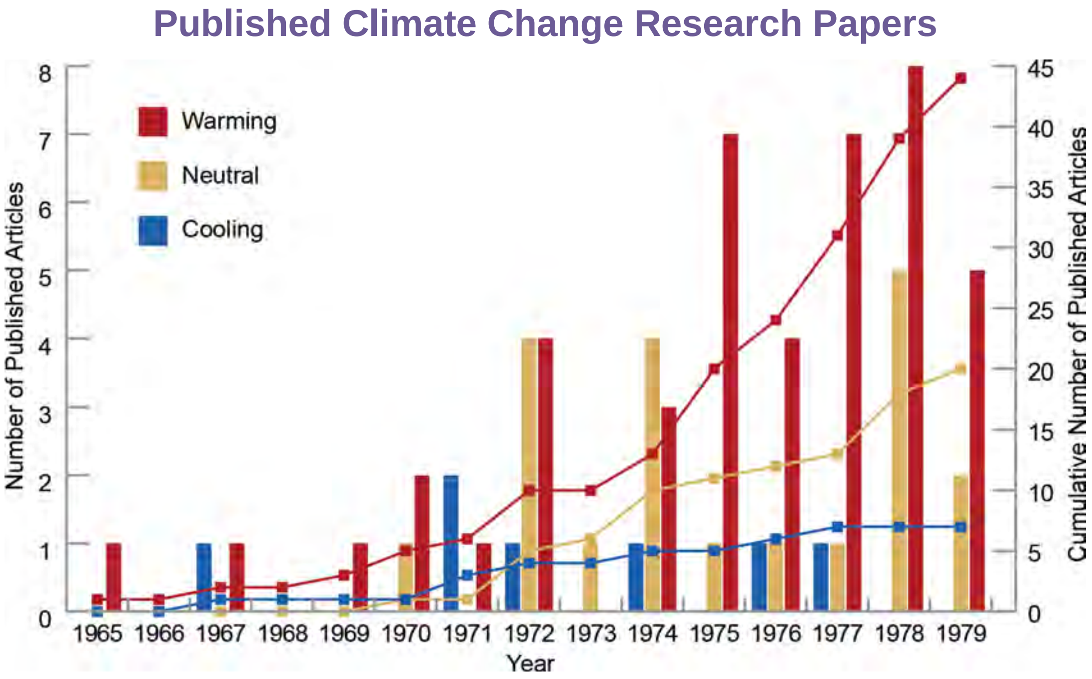


Figure A5.9: This chart compares the number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories published from 1965 to 1979. The bars indicate the number of articles published per year. The lines with squares indicate the cumulative number of articles published. Over this period the literature survey found 7 papers suggesting future cooling (blue line), 20 neutral (yellow line), and 44 warming (red line). Source: Peterson et al. 2008.[16]

How are temperature and precipitation patterns projected to change in the future?

Our world will continue to warm in the future because of historic emissions of greenhouse gases (GHGs), but the amount of warming will depend largely on the level of future emissions of GHGs and the choices humans make. If humans continue burning fossil fuels at or above our current rate through the end of the century, scientists project Earth will warm about 9°F, relative to preindustrial times (prior to 1750). Precipitation is projected to still be seasonally and regionally variable, but on average, projections show high-latitude areas getting wetter and subtropical areas getting drier. The frequency and intensity of very heavy precipitation are expected to increase, increasing the likelihood of flooding. Climate change will not affect all places in the same way or to the same degree but will vary at regional levels.

In the coming decades, scientists project that global average temperature will continue to increase (Ch. 2: Climate), although natural variability will continue to play a significant role in year-to-year changes. Sizeable variations from global average changes are possible at the regional level. Even if humans drastically reduce levels of GHG emissions, near-term warming will still occur because there is a lag in the temperature response to changes in atmospheric composition (Figure A5.10).

Over the next couple decades, natural variability and the response of Earth's climate system to historic emissions will be the primary determinants of observed warming. After about 2050, however, the rate and amount of emissions of GHGs released by human activities, as well as the response of Earth's climate system to those emissions, will be the primary determining factors in changes in global and regional temperature (Figure A5.13) (see also Ch. 2: Climate). Efforts to rapidly and significantly reduce emissions of GHGs can still limit the global temperature increase to 3.6ºF (2ºC) by the end of the century relative to preindustrial levels.[17]

Precipitation patterns are also expected to continue to change throughout this century and beyond. The trends observed in recent decades are expected to continue, with more precipitation projected to fall in the form of heavier precipitation events.[3] Such events increase the likelihood of flooding, even in drought-prone areas. As with increases in global average temperature, large-scale shifts towards wetter or drier conditions and the projected increases in heavy precipitation are expected to be greater under higher GHG emissions scenarios (for example, RCP8.5) versus lower ones (for example, RCP4.5). Projected warming is also expected to lead to an increase in the fraction of total precipitation falling as rain rather than snow, which reduces snowpack on the margins of areas that now have reliable snowpack accumulation during the cold season (see, for example, Ch. 24: Northwest, KM 2).

Observed and Projected Changes in Global Temperature

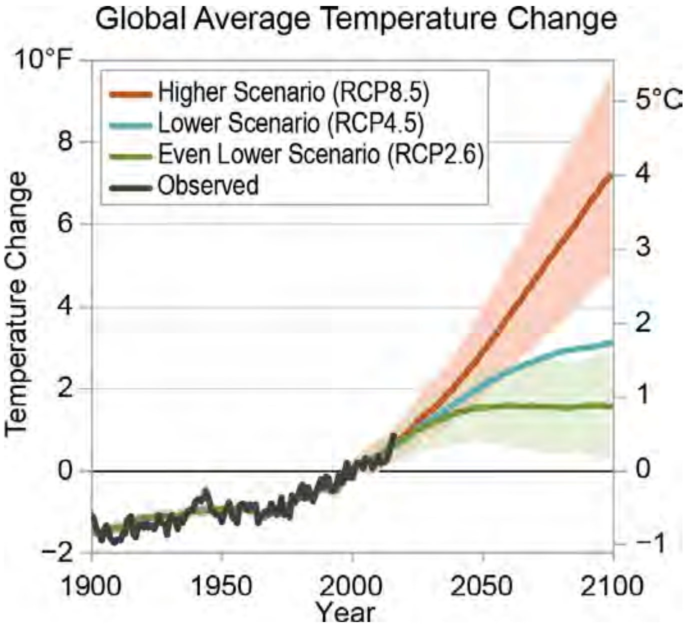


Figure A5.10: This figure shows both observed and projected changes in global average temperature. Under a representative concentration pathway (RCP) consistent with a higher scenario (RCP8.5; red) by 2080–2099, global average temperature is projected to increase by 4.2°–8.5°F (2.4°–4.7°C; burnt orange shaded area) relative to the 1986–2015 average. Under a lower scenario (RCP4.5; blue) global average temperature is projected to increase by 1.7°–4.4°F (0.9°–2.4°C; range not shown on graph) relative to 1986–2015. Under an even lower scenario (RCP2.6; green) temperature increases could be limited to 0.4°–2.7°F (0.2°–1.5°C; green shaded area) relative to 1986–2015. Limiting the rise in global average temperature to less than 2.2°F (1.2°C) relative to 1986–2015 is approximately equivalent to 3.6°F (2°C) or less relative to preindustrial temperatures. Thick lines within shaded areas represent the average of multiple climate models. The shaded regions illustrate the 5% to 95% confidence intervals for the respective projections. Source: adapted from Wuebbles et al. 2017.[4]

How do computers model Earth's climate?

Global climate models enable scientists to create "virtual Earths," where they can analyze causes and effects of past changes in temperature, precipitation, and other climate variables. Today's climate models can accurately reproduce broad features of past and present climate, such as the location and strength of the jet stream, the spatial distribution and seasonal cycle of precipitation, and the natural occurrence of extreme weather events, such as heat and cold waves, droughts and floods, and hurricanes. They also can reproduce historic natural cycles, such as the periodic occurrence of ice ages and interglacial warm periods, as well as the human-caused warming that has occurred over the last 50 years. While uncertainties remain, scientists have confidence in model projections of how climate is likely to change in the future in response to key variables, such as an increase in human-caused emissions of greenhouse gases, in part because of how accurately they can represent past climate changes.

Climate models are based on equations that represent fundamental laws of nature and the many processes that affect Earth's climate system. By dividing the atmosphere, land, and ocean into smaller spatial units to solve the equations, climate models capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over longer time frames, these models simulate wind patterns, high- and low-pressure systems, ocean currents, ice and snowpack accumulation and melting, soil moisture, extreme weather occurrences, and other environmental characteristics that make up the climate system (Figure A5.11).[18]

Some important processes, including cloud formation and atmospheric mixing, are represented by approximate relationships, either because the processes are not fully understood or they are at a scale that a model cannot directly represent. These approximations lead to uncertainties in model simulations of climate. Approximations are not the only uncertainties associated with climate models, as discussed in the FAQ "What are key uncertainties when projecting climate change?"

Comparison of Climate Models and Observed Temperature Change

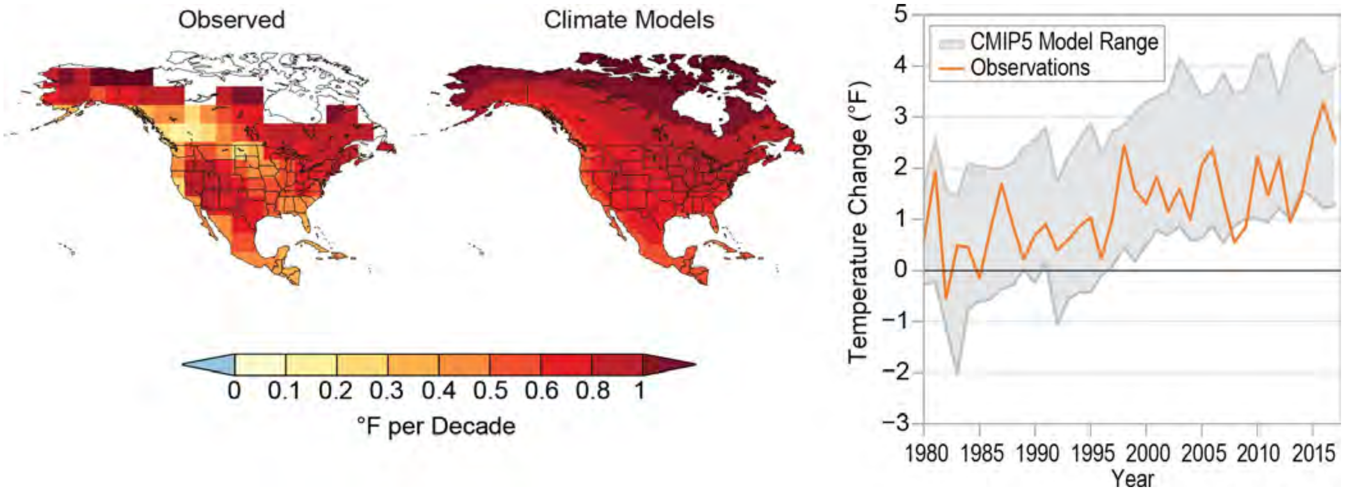


Figure A5.11: Climate simulations (right map) can capture the approximate geographical patterns and magnitude of the surface air temperature trend seen in observational data for the period 1980–2017 (left map). The warming pattern seen in the right map is an average based on 43 different global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The graphical representation shows the range of temperature changes simulated by the models for North America (relative to 1901–1960; gray shading, 5th to 95th percentile range) overlaid by the observed annual average temperatures over North America (orange line). The observed temperature changes are a result of both human contributions to recent warming and natural temperature variations. Averaging the simulations from multiple models suppresses the natural variations and thus shows mainly the human contribution, which is part of the reason small-scale details are different between the two maps. Sources: (maps) adapted from Walsh et al. 2014[6] (and graph) NOAA NCEI and CICS-NC.

Can scientists project the effects of climate change for local regions?

Yes, though there are limitations. With advances in computing power, the future effects of climate change can be projected more accurately for local communities. Local high-resolution (downscaled) climate modeling can be used to produce data at a scale of 1-20 miles. These downscaled projections show climate-related impacts at the local level and can be an important tool for community planners and decision-makers.

One significant research focus recently has been to develop models of climate impacts on a relatively small geographic scale. Most global climate projections use grid units that may be too coarse to properly represent mountains, coastlines, and other important features of a local landscape. Recently, two different approaches have been used by scientists to project local climate conditions.

The first is a statistical approach that uses local observations in conjunction with global models to project future changes. The local observations required for this approach are available only for limited regions and for a few climate variables (mainly temperature and precipitation; Figure A5.12).

The second method is a so-called dynamical approach that uses an additional high-resolution computer model—similar to a weather prediction model— to account for complex topography and varying land cover that can impact climate on the local level. High-resolution dynamical models are complete enough to simulate numerous climate variables (temperature, precipitation, winds, humidity, surface sunlight, etc.) and do not require the local observations required for the statistical approach. However, these models require an immense amount of computing power. Today's most powerful supercomputers enable climate scientists to examine the effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase 100-fold or more, improving climate projections and models on both the global and local levels.

It should also be noted that both statistical and dynamical approaches have biases and errors that, when combined with uncertainties from global model simulations, can reduce the level of confidence in these more localized projections (see Hayhoe et al. 2017[18] for more details).

Climate Modeling for Smaller Regions

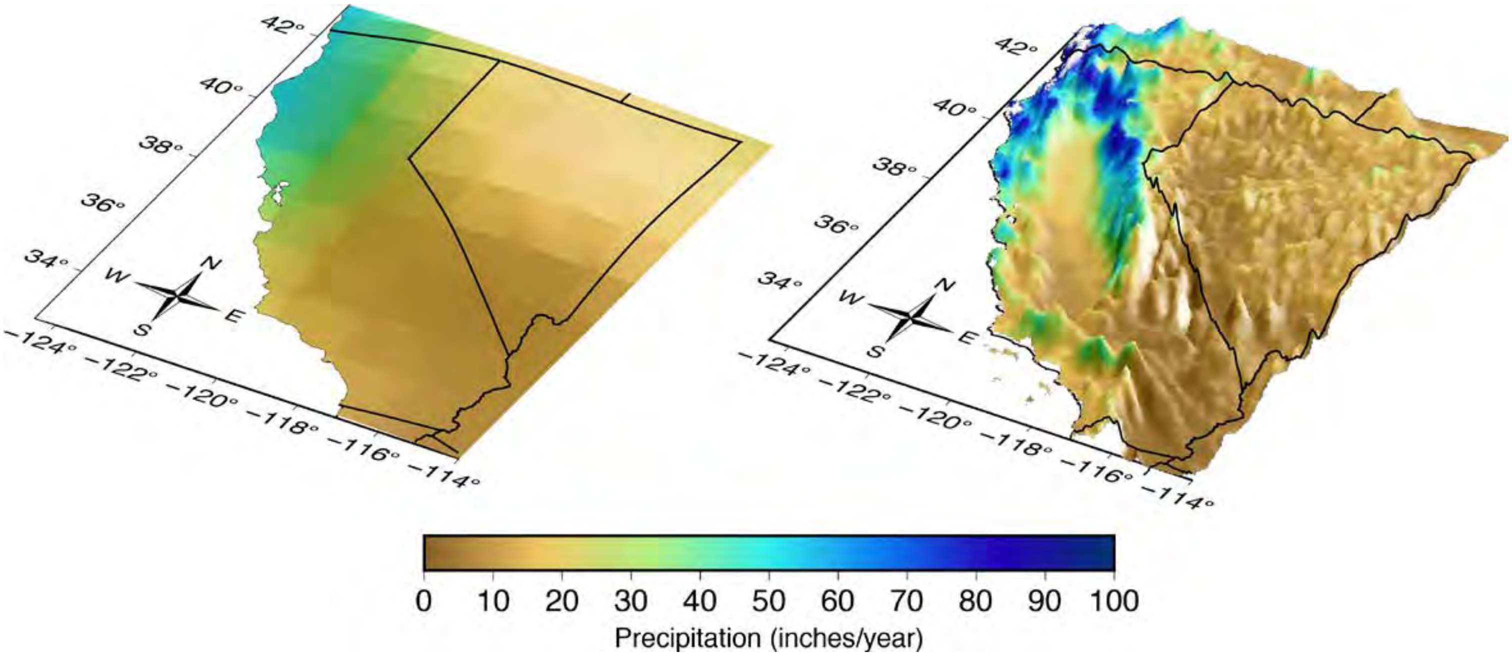


Figure A5.12: The figure shows projections of annual precipitation (in inches) in California and Nevada in a global climate model with a resolution of 100 miles (left) and, after using a statistical model to account for the effects of topography, at a resolution of 3.6-miles (right). The global model has only a few grid cells over the entire state of California, so it does not resolve the coastal mountain range, interior valley, or Sierra Nevada on the border with Nevada. The precipitation field in the right panel, by contrast, captures the wet conditions on the west slopes of the mountains and the dry, rain shadow region to the east of the mountains. The topography has been exaggerated for clarity and by the same amount in both panels. Source: UCSD Scripps Institute of Oceanography.

What are key uncertainties when projecting climate change?

The precise amount of future climate change that will occur over the rest of this century is uncertain, mainly due to uncertainties in emissions, natural variability, and differences in scientific models.

First, projections of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change due to changes in population, energy use, technology, and economics. Society may choose to reduce emissions or continue on a pathway of increasing emissions. The differences in projected future climate under different scenarios are generally small for the next few decades. By the second half of the century, however, human choices, as reflected in these scenarios, become the key determinant of future climate change (Figure A5.13).

A second source of uncertainty is natural variability, which affects the climate over timescales from months to decades. These natural variations are largely unpredictable, such as a volcanic eruption, and are superimposed on the warming from increasing greenhouse gases (GHGs).

A third source of uncertainty involves limitations in our current scientific knowledge. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and aerosol effects). Additionally, climate sensitivity, or how much the climate will warm with a given increase in GHGs (often a doubling of GHG from preindustrial levels), is still a major source of uncertainty. As a result, different models produce small differences in projections of global average change. Scientists often use multiple models to account for the variability and represent this as a range of projected outcomes.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in projections of climate in the future. For example, as the Arctic warms, carbon trapped in permafrost may be released into the atmosphere, increasing the initial warming due to human-caused emissions of GHGs, or an ice sheet may collapse, leading to faster than expected sea level rise.

However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, with those bounds determined not only from the differences in how climate responds to a doubling of GHG concentrations among models but also by utilizing information about climate changes in the past (see Hayhoe et al. 2017[18] for more details).

Key Uncertainties in Temperature Projections

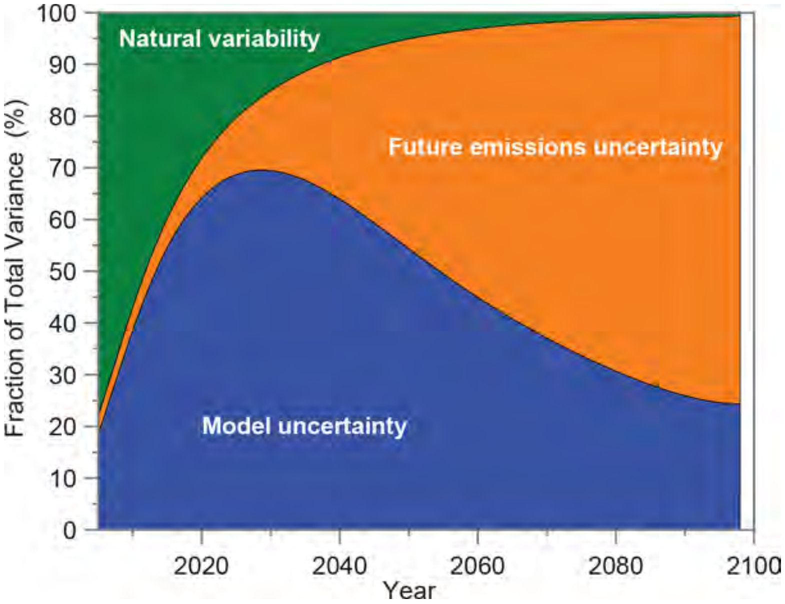


Figure A5.13: The graph shows the change in the fraction of total variance (uncertainty) of three components of total uncertainty in decadal average surface air temperature projections for the contiguous United States. Green represents natural variability, orange represents future emissions uncertainty, and blue represents model or scientific uncertainty (including in climate sensitivity). As the time period becomes more distant, the impact of natural variability becomes less significant due to the smaller variability over a larger period. Future emissions uncertainty increases as time progresses, since we are unable to determine the exact choices that will be made by humans in the future. The influence of model uncertainty on the total uncertainty of how climate will change decreases as the century progresses, due to advances in science and the creation of more accurate and precise assessment systems. This figure shows total uncertainty for the lower 48 states—as the size of the region is reduced, the relative importance of natural variability increases. It is important to note that this figure shows the fractional sources of uncertainty. The total amount of uncertainty increases through time. Source: adapted from Hawkins and Sutton 2009.[19] ©American Meteorological Society. Used with permission.

Is it getting warmer everywhere at the same rate?

Our world is warming overall, but temperatures are not increasing at the same rate everywhere. The average global temperature is projected to continue increasing throughout the remainder of this century due to greenhouse gas (GHG) emissions from human activities. Generally, high latitudes are expected to continue warming more than lower latitudes; coastal and island regions are expected to warm less than interior continent regions.

Temperature changes at a given location are a function of multiple factors, including global and local forces, and both human and natural influences. Though Earth's average temperature is rising, some locations could be cooling due to local factors. In some places, including the U.S. Southeast, temperatures do not show a warming trend over the last century as a whole, although they have been increasing since the 1960s (Ch. 19: Southeast). Possible causes of the observed lack of warming in the Southeast during the 20th century include increased cloud cover and precipitation, increases in the presence of fine particles (called aerosols) in the atmosphere, expanding forests, decreases in the amount of heat conducted from land due to increases in irrigation, and multidecadal variability in sea surface temperatures in both the North Atlantic and the tropical Pacific Oceans. At smaller geographic scales and time intervals, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale. A lack of warming or a decrease in temperature at an individual location does not negate the fact that, overall, the planet is warming.

Alaska, in contrast to the U.S. Southeast, has been warming twice as fast as the global average since the middle of the 20th century (Ch. 26: Alaska). Statewide average temperatures for 2014–2016 were notably warmer as compared to the last few decades, with 2016 being the warmest on record. Daily record high temperatures in the contiguous United States are now occurring twice as often as record low temperatures. In Alaska, starting in the 1990s, record high temperatures occurred three times as often as record lows, and in 2015, an astounding nine times as often (Ch. 26: Alaska).

Because Earth's climate system still has more energy entering than leaving, global warming has not yet equilibrated to the load of increased GHGs that have already accumulated in the atmosphere (for example, the oceans are still warming over many layers from surface to depth). Some GHGs have long lifetimes (for example, carbon dioxide can reside in the atmosphere for a century or more). Thus, even if the emissions of GHGs were to be sharply curtailed to bring them back to natural levels, it is estimated that Earth is committed to continued warming of more than 1°F by 2100.

At the global scale, some future years will be cooler than the preceding year; some decades could even be cooler than the preceding decade (Figure A5.14). Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future as a result of natural variability and other factors. Nonetheless, each successive decade in the last 30 years has been the warmest in the period of reliable instrumental records (going back to 1850; Figure A5.15). In fact, the rate of warming has accelerated in the past several decades, and 17 of the 18 warmest years have occurred since 2001 (see FAQ "What do scientists mean by the 'warmest year on record'?"). Based on this historical record and assessed scenarios for the future, it is expected that future global temperatures, averaged over climate timescales of 30 years or more, will be higher than preceding periods as a result of emissions of CO_2 and other GHGs from human activities (Ch 2: Climate).

Temperature Change Varies by Region

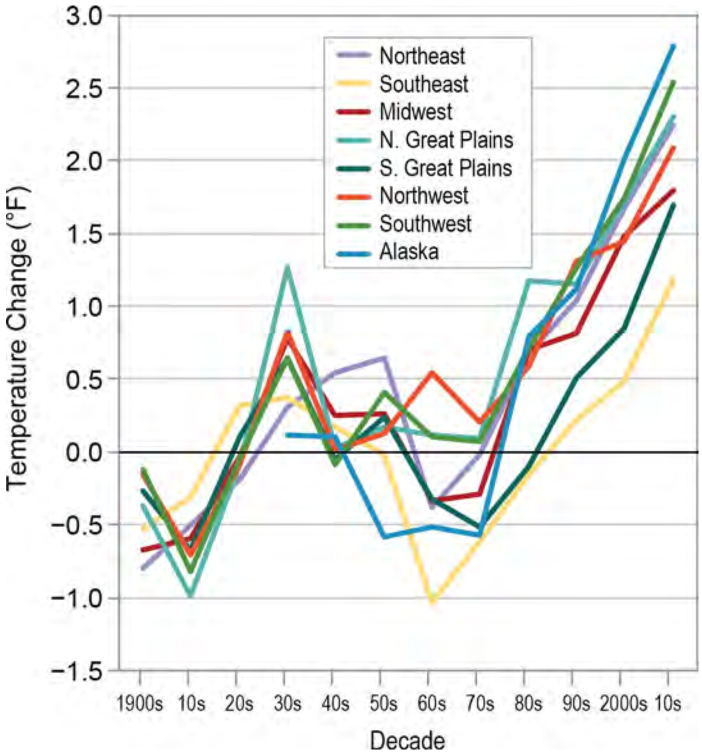


Figure A5.14: This graph shows changes in decadal-averaged temperature relative to the 1901–1960 average for eight of the ten NCA regions (see Front Matter, Figure 1). This figure shows how regional temperatures can be quite variable from decade to decade. All regions, however, have experienced warming over the last three decades or more. The most recent decade, the 2010s, refers to the 6-year period of 2001–2016. Source: adapted from Walsh et al. 2014.[6] Comparable data is not currently available for the Hawai'i and U.S-Affiliated Pacific Islands or U.S. Caribbean regions.

Average Global Temperature Is Increasing

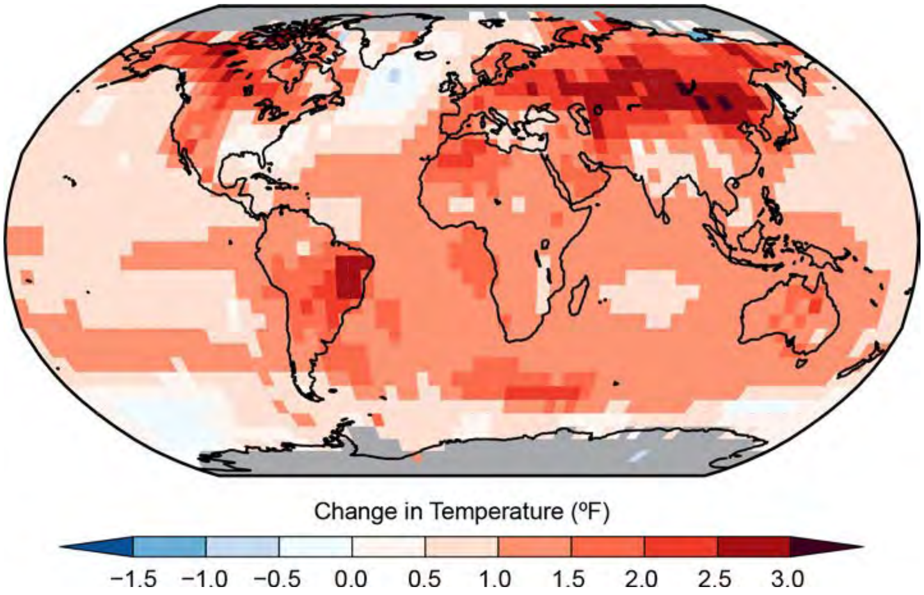


Figure A5.15: This map shows the observed changes in temperature for the 1986 to 2015 period relative to the 1901–1960 average. Shades of red indicate warming, while shades of blue indicate cooling. There are insufficient data in the Arctic Ocean and Antarctica for computing long-term changes. There are substantial regional variations in trends across the planet, though the overall trend is warming. Source: Vose et al. 2012.[20]

What do scientists mean by the "warmest year on record"?

When scientists declare it the "warmest year on record," they mean it's the warmest year since modern global surface temperature record keeping began in 1880. Global temperature data from NASA show that 2016 marked the sixth time this century that a new record high annual average temperature was set (along with 2002, 2005, 2010, 2014, and 2015) and that 17 of the 18 warmest years have occurred since 2001.

The "warmest year on record" means it is the warmest year in more than 130 years of modern record keeping of global surface temperature. Prior to 1880, observations did not cover a large enough area of Earth's surface to enable an accurate calculation of the global average temperature. To calculate the value in recent times, scientists evaluate data from roughly 6,300 stations around the world, on land, ships, and buoys.

The year the last National Climate Assessment was published, 2014, was the warmest year on record at the time, but it was surpassed by 2015, which was then surpassed by 2016. Data from NASA shows that 17 of the 18 warmest years have occurred since 2001, and the 6 warmest years on record have occurred this century (Figure A5.16). However, the global surface temperature is affected by natural variability in addition to climate change, so it is not expected that each year will set a new temperature record.

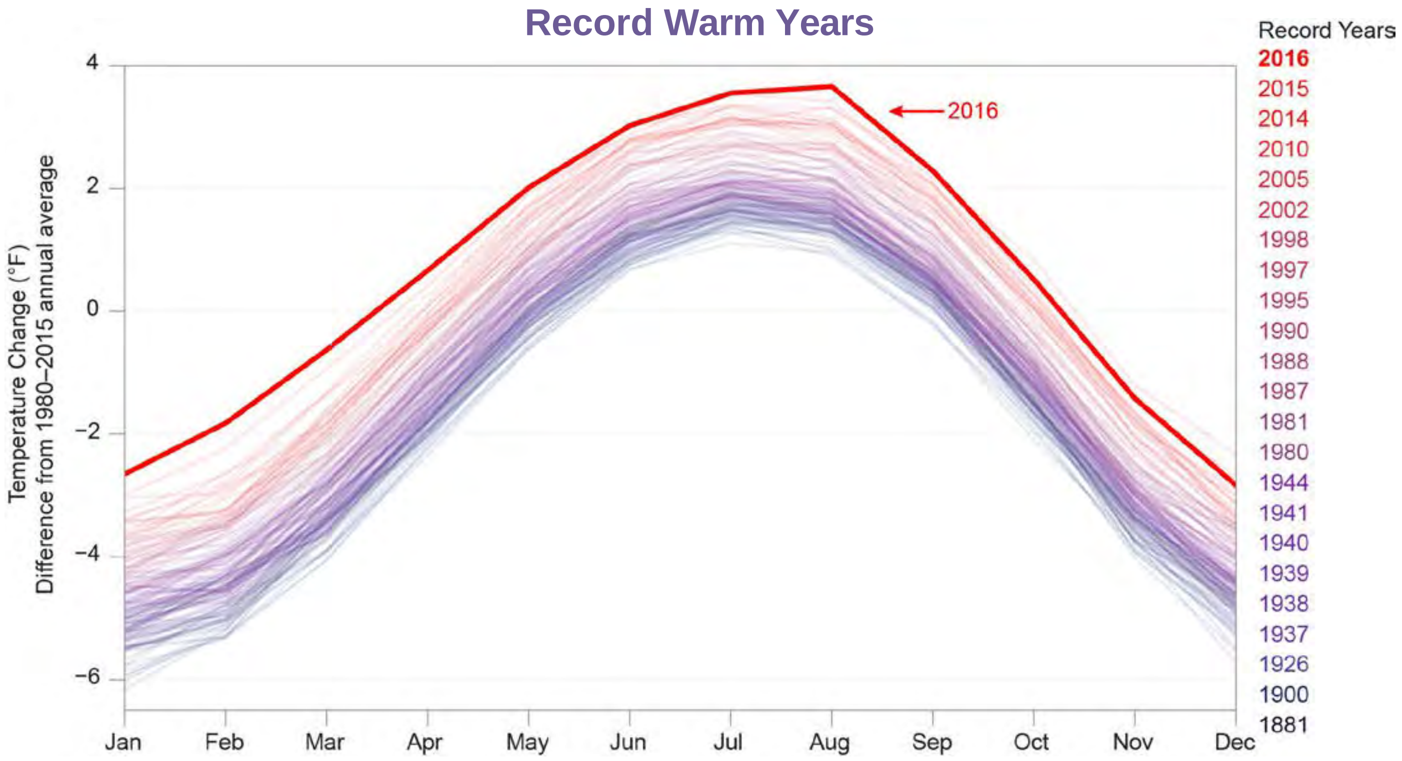


Figure A5.16: This graph shows global, monthly averaged temperature, relative to the 1980–2015 average, plotted over annual temperature cycles from 1880–2017. Record-breaking warm years are listed in the column to the right. The colored lines, shading from gray to blue to purple to red, indicate the years from 1880 to 2017, with 2016, bolded in red, being the hottest year on record. An animation of the complete time series is available online at https://nca2018.globalchange.gov/chapter/appendix-5/#fig-a5-16. Source: NASA.

How do climate projections differ from weather predictions?

The range of possible weather conditions at a specific location on any given day can vary considerably. The climate varies far less for that same location, because it is a measure of weather conditions averaged over 30 years or more. Because the range of possible climate conditions at a given location is much smaller than the range of possible weather conditions, scientists are able to project climate conditions decades into the future.

Projecting how climate may change decades in the future is a different scientific issue than forecasting weather a few days from now. Weather prediction means determining the exact location, time, and magnitude of specific events. Because the range of possible weather conditions can vary so widely, the weather forecast is extremely sensitive to even the smallest uncertainties or errors in our description of the state of the atmosphere at the start of a forecast. The impact of those uncertainties magnifies over time, which makes it very difficult to predict specific weather events at a given location more than a week or two into the future.

Because climate is the average weather at a given location over long periods of time (three decades or more), the range of possible climate conditions at a given location is much smaller than the range of possible weather conditions. For example, the daytime high temperature at a given location may vary by 30°F or more over the course of a day, while the annual average temperature over 30 years may vary by no more than a few degrees (Figure A5.17).

We can project how climate may change over time in response to natural forces, such as changes in incoming solar radiation, and in response to human activities, such as increasing the abundance of greenhouse gases (GHGs) or decreasing particle pollution. These projections are usually expressed in terms of probabilities describing a range of possible outcomes, not in the sort of exact (deterministic) language of many weather forecasts.

The difference between predicting weather and projecting climate is sometimes illustrated with a public health analogy. While it is impossible for us to determine the exact date and time when a particular individual will die, we can easily calculate the average age of death of all Americans for a time period in the past. In this case, weather is like the individual, while climate is like the average. To extend this analogy into the realm of climate change, we can also calculate the average life expectancy of Americans who smoke. We can predict that, on average, smokers will not live as long as nonsmokers. Similarly, we can project what the climate will be like if we emit lower levels of GHGs and what it will be like if we emit more.

U.S. Annual Average Temperature

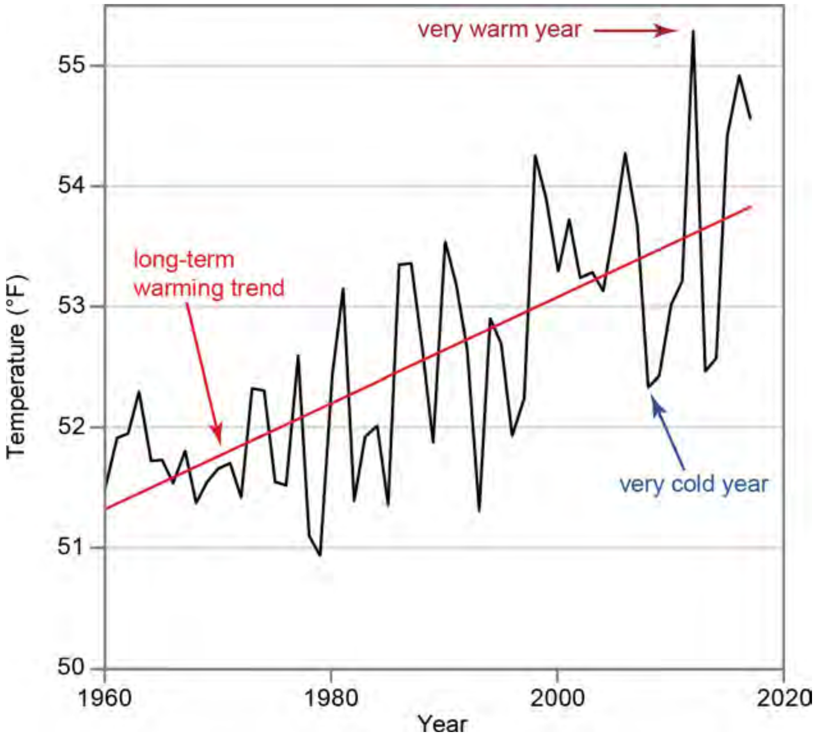


Figure A5.17: This figure shows the annual average surface temperature for the contiguous U.S. (black line) from 1960 to 2017, and the long-term warming trend (red line). Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. Year-to-year and even decade-to-decade, conditions do not necessarily tell us much about long-term changes in climate. One cold year, or even a few cold years in a row, does not contradict a long-term warming trend, just as one hot year does not prove it. Source: adapted from Walsh et al. 2014.[6]

Climate, Weather, and Extreme Events

Was there a “hiatus” in global warming?

Temperature records show that the long-term (30 years or longer) trend in increasing surface temperatures has not ceased. The rate of warming has been faster during some decades and slower during others, but these relatively short periods of time are not the basis for scientists’ conclusion that sustained global warming is occurring.

“Global warming” refers to the increase in global average surface temperature that has been observed for more than a century. This warming is clearly revealed in both the surface temperature record and in satellite measurements of lower-atmospheric (troposphere) temperature. While the long-term trend shows warming, scientists expect that the rate of warming will vary from year to year or decade to decade due to the variability inherent in the climate system, or due to short-term changes in climate forcings, such as aerosols (dust, pollution, or volcanic particles) or incoming solar energy (Figure A5.18).

Temporary slowdowns in the rate of warming have occurred earlier in the historical record, even as carbon dioxide concentrations continued to rise. Temporary speedups have also occurred, most notably from the early 1900s to the 1940s and from the 1970s to the late 1990s. Computer simulations of both historical and future climate produce similar variations in the rate of warming, making recent variations in short-term temperature trends unsurprising.

From the mid-1940s to the mid-1970s, there was almost no increase in global temperature, possibly related to an increase in volcanic activity and/or human-caused aerosol emissions. Most notably, for the 15 years following the 1997–1998 El Niño event, the observed rate of temperature increase was smaller than what was projected by some climate models. However, during this peri- od other indicators of climate change continued previous trends associated with warming, such as increasing ocean heat content and decreasing arctic sea ice extent (Figure A5.19; see Wuebbles et al. 2017,[4] Box 1.1).

Short-Term Variability Versus Long-Term Trend

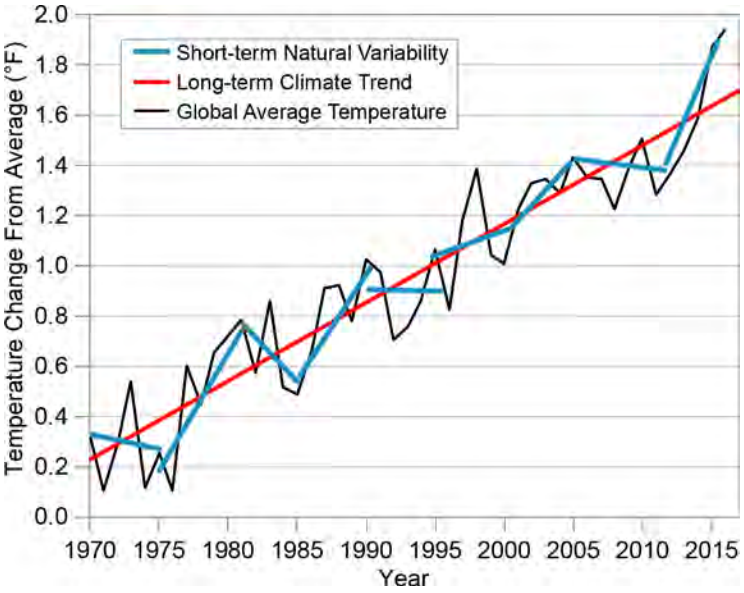


Figure A5.18: Short-term trends in global temperature (blue lines show approximate temperature trends at five-year intervals) can range from decreases to sharp increases. The evidence of climate change is based on long-term trends over 30 years or more (red line). The black line shows the annual average change in global surface temperature from 1970 to 2016 relative to 1901–1960. Source: adapted from Walsh et al. 2014.[6]

Speedups and Slowdowns in Warming

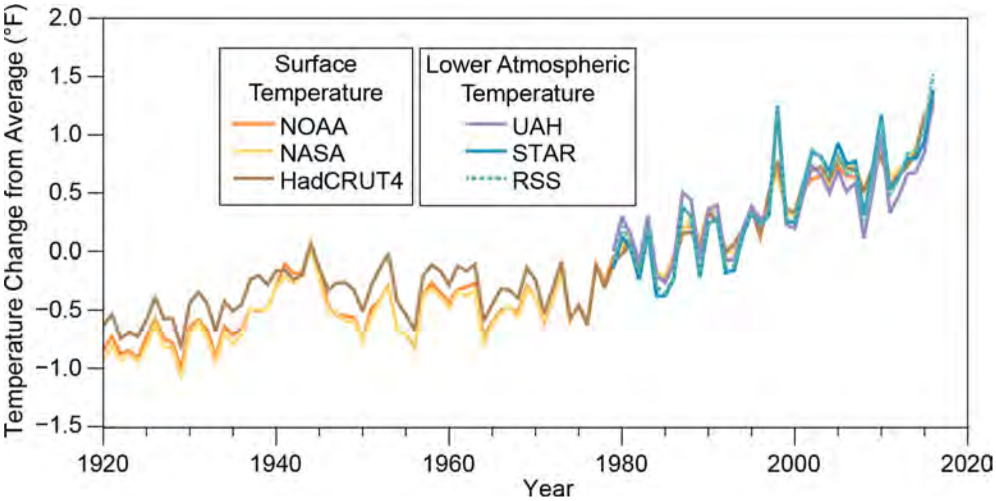


Figure A5.19: The figure shows global annual average surface temperatures (datasets are from NOAA [orange], NASA [yellow], and the United Kingdom's Met Office/University of East Anglia [HadCRUT4, brown]) and lower-atmospheric (tropospheric) temperatures (datasets are from University of Alabama–Huntsville [purple], NOAA [blue], and Remote Sensing Systems [blue dashed]) as compared to 1900–1960 averages. Decades of relatively faster or slower warming are observed within the long-term warming trend. Source: adapted from Trenberth 2015.[21]

What is an extreme event?

An extreme event is a weather or climate-related event that is particularly rare for a given time of year and location. These events include drought, wildfires, floods, severe storms (including hurricanes), heat waves, cold snaps, and heavy rains, and they can have devastating impacts on local communities, infrastructure, the economy, and the environment.

Scientists determine if an event is extreme or not by comparing measurements of weather and climate variables (rainfall, wind speed, temperature, etc.) with thresholds. Events above or below these thresholds are considered rare occurrences, such as events that rank in the highest or lowest 5% of observed values. Several thresholds may be used to define if a single event is considered extreme, and the threshold may change depending on the period of interest (day, month, season, year, etc.) and the chosen reference period (for example, 1961–1990 versus 1900–2000).

It is possible for a single event to meet the definition of an extreme event but not have a large impact. Conversely, it is possible for several types of events that may not be considered extreme individually to cause catastrophic impacts when taken together, such as a sequence of hot days that occur during dry conditions that worsen a drought, or several rainfall events occurring one after another that produce flooding (see Wuebbles et al. 2017, Knutson et al 2017, and Kossin et al. 2017 for more detail on extreme events[4,14,22]).

Have there been changes in extreme weather events?

Yes. Climate change can and has altered the frequency, intensity, duration, or timing of certain types of extreme weather events when compared to past time periods. The harmful effects of severe weather raise concerns about how climate change might alter the risk of such events.

While there have always been extreme events due to natural causes, the frequency and severity of some types of events have increased due to climate change (Figure A5.20) (see also Ch. 2: Climate). As average temperatures have warmed due to emissions of greenhouse gases (GHGs) from human activities, extreme high temperatures have become more frequent and extreme cold temperatures less frequent. From 2001 to 2012, more than twice as many daily high temperature records, as compared to low temperature records, were broken in the United States. With continued increases in the level of GHGs in the atmosphere, the chances for extreme high temperature will continue to increase, with the occurrence of extreme low temperatures becoming less common. Even with much warmer average temperatures later in the century, there may still be occasional record cold snaps, though occurrences of record heat will be more common.

Because warmer air can hold more moisture, heavy rainfall events have become more frequent and severe in some areas and are projected to increase in frequency and severity as the world continues to warm. Both the intensity and rainfall rates of Atlantic hurricanes are projected to increase (see, for example, Ch. 2: Climate, Box 2.5), with the strongest storms getting stronger in a warming climate. Recent research has shown how global warming can alter atmospheric circulation and weather patterns such as the jet stream, affecting the location, frequency, and duration of these and other extremes.[13]

More research would be required to improve scientific understanding of how human-caused climate change will affect other types of extreme weather events important to the United States, such as tornadoes and severe thunderstorms. These events occur over much smaller scales of time and space, which makes observations and modeling more challenging. Projecting the future influence of climate change on these events can also be complicated by the fact that some of the risk factors for these events may increase while others may decrease.[2,4,22]

Extreme Temperature and Precipitation Events

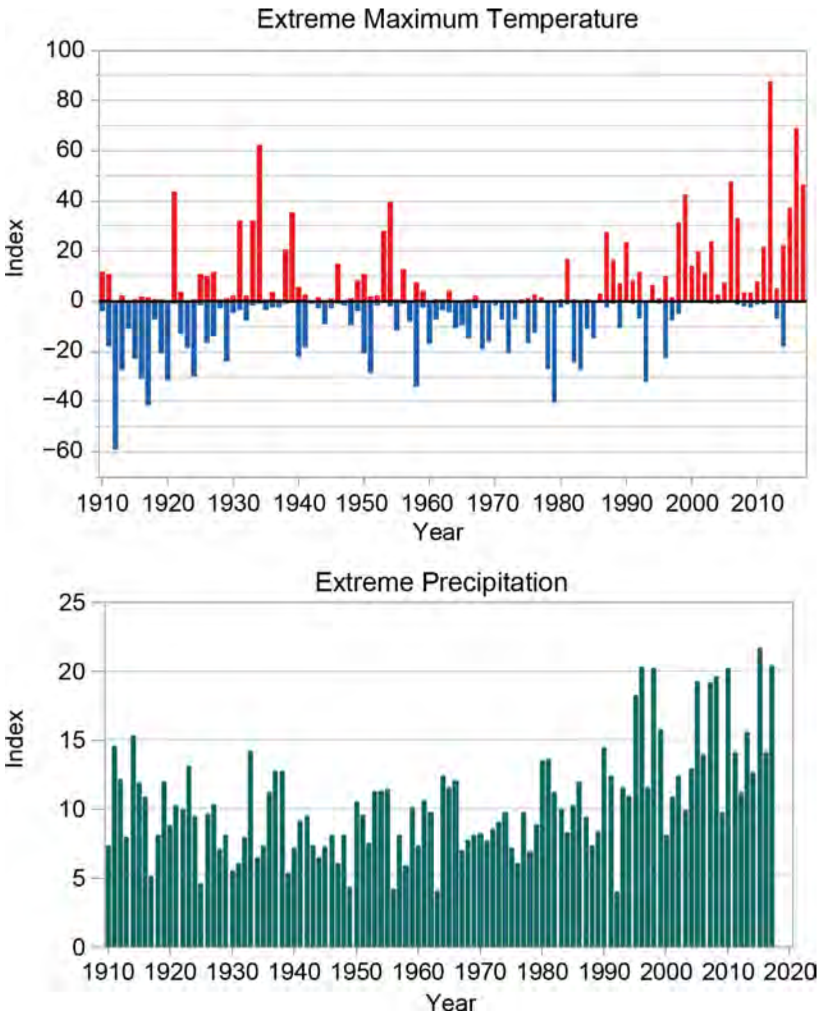


Figure A5.20: The top panel shows the percentage of land area in the contiguous United States that experienced maximum temperatures greatly above or below normal (upper or lower 10th percentile, respectively). The bottom panel shows the percentage of the land area for the contiguous United States that experienced extreme 1-day precipitation amounts that were greatly above normal. In the past 25 years, a much greater area of the country has experienced warmer extreme maximum temperatures and extreme rainfall. Sources: NOAA NCEI and CICS-NC.

Can specific weather or climate-related events be attributed to climate change?

While it is difficult to attribute a specific weather or climate-related event to any one cause, climate change can affect whether an event was more or less likely to occur. Climate change can also influence the severity of these events. Our ability to detect the influence of human-caused warming on particular kinds of extreme events depends both on the length and quality of our historical records of those events, as well as how well we can simulate the environmental processes that produce and sustain them.

Extreme event attribution is a relatively recent scientific advancement that seeks to determine whether climate change altered the likelihood of occurrence of a given extreme event.[14,23] A long-term, high-quality record of a given type of event and a computer model capable of producing a realistic simulation of the event are needed in order to assess the influence of climate change. Because of these data and modeling constraints, our ability to detect the influence of human-caused global warming on heat waves and, to a lesser extent, heavy rainfall events is better at present than our ability to detect its influence on tornadoes or hurricanes. As scientists collect more data and develop more advanced tools, they will be able to better quantify cause-and-effect relationships in the climate system, which should improve their ability to attribute how much human-caused climate change contributes to specific weather and climate-related events.

One example of event attribution comes from the recent California drought, where scientists found that human-caused climate change contributed 8%–27% to the severity of the drought.[24] Droughts are frequent in the Southwest and occur regardless of human activity, but human-caused climate change leads to increased evaporation and decreased soil moisture, intensifying droughts during periods of little rain.[14]

Could climate change make Atlantic hurricanes worse?

Atlantic hurricane activity has increased since the 1970s, but the relatively short length of high-quality hurricane records does not yet allow us to say how much of that increase is natural and how much may be due to human activity. With future warming, hurricane rainfall rates are likely to increase, as will the number of very intense hurricanes, according to both theory and numerical models. However, models disagree about whether the total number of Atlantic hurricanes will increase or decrease. Rising sea level will increase the threat of storm surge flooding during hurricanes.

Hurricane activity is undeniably linked to sea surface temperatures (see Ch. 2: Climate, Box 2.5 for a discussion on the 2017 Atlantic hurricane season). Other influences being equal, warmer waters yield stronger hurricanes with heavier rainfall. The tropical Atlantic Ocean has warmed over the past century, at least partly due to human-caused emissions of greenhouse gases. However, high-quality records of Atlantic hurricanes are too short to reliably separate any long-term trends in hurricane frequency, intensity, storm surge, or rainfall rates from natural variability.[22] This does not mean that no trends exist, only that the data record is not long enough to determine the cause.

Most models agree that climate change through the 21st century is likely to increase the average intensity and rainfall rates of hurricanes in the Atlantic and other basins. Models are less certain about whether the average number of storms per season will increase or decrease. Early modeling raised the possibility of a significant future increase in the number of Category 4 and 5 storms in the Atlantic (Figure A5.21). While that remains possible, the most recent high-resolution modeling provides mixed messages: some models project increases in the number of the basin's strongest storms, and others project decreases.[22]

Regardless of any human-influenced changes in storm frequency or intensity, rising sea level will increase the threat of storm surge flooding during hurricanes (Ch. 8: Coastal; Ch. 18: Northeast; Ch. 19: Southeast; Ch. 20: U.S. Caribbean; Ch. 23: S. Great Plains).

Category 4 and 5 Hurricane Formation: Now and in the Future

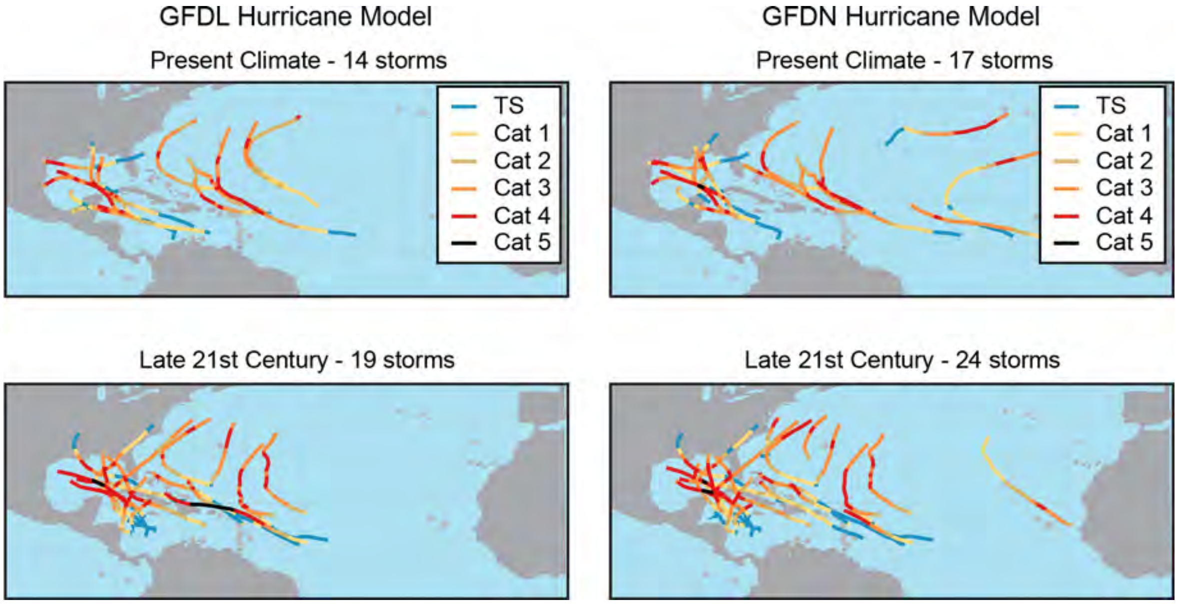


Figure A5.21: These maps show computer-simulated tracks and intensities of hurricanes reaching Categories 4 and 5 (intensity based on wind speeds ranging from TS for tropical storm strength up to Category 1 through Category 5 hurricanes). The top panels show hurricane tracks from two different models under current climate conditions (1980–2006). The bottom panels show projections from the same models but for late-21st century (2081–2100) conditions, both under the lower scenario (RCP4.5). These projections show an increase in the frequency of Category 4 and 5 hurricanes, with a higher tendency of these storms to shift towards the Gulf of Mexico, Florida, and the Caribbean (as opposed to remaining in the open Atlantic Ocean). Source: adapted from Knutson et al. 2013.[25] ©American Meteorological Society. Used with permission.

Societal Effects

How is climate change affecting society?

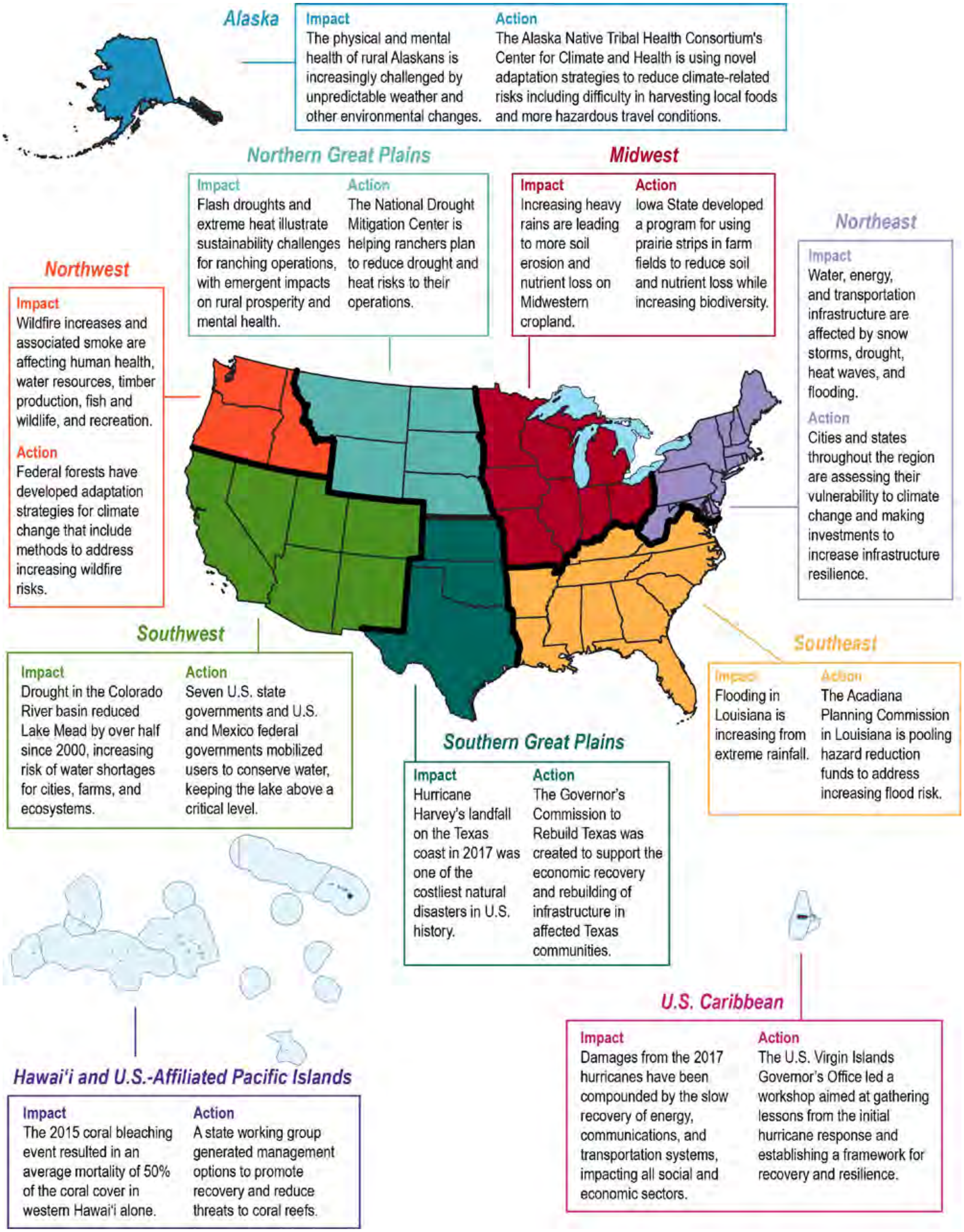
Climate change is altering the world around us in ways that become increasingly evident with each passing decade. Natural and human systems that we rely on are being impacted by more intense precipitation events, rising sea level, and a warming ocean and will be impacted by projected increases in the frequency of droughts and heat waves and other extreme weather patterns.

Many people are already being affected by the changes that are occurring, and more will be affected as these changes continue to unfold (Figure A5.22). In the Northeast and Northwest, fishing communities have to adapt to increasing ocean temperatures and acidification that impact fish and shellfish (Ch. 9: Oceans; Ch. 18: Northeast; Ch. 24: Northwest). Coastal communities, especially those located on islands, will need to confront rising sea levels, which are already contaminating freshwater supplies, flooding streets during high tides, and exacerbating storm surge flooding (Ch. 8: Coastal; Ch. 19: Southeast; Ch. 20: U.S. Caribbean; Ch. 27: Hawai'i and Pacific Islands). Shifts in the timing of the seasons and changes in the location of plants and animals affect communities dependent on those resources for tourism, economy, and/or cultural purposes (Ch. 7: Ecosystems; Ch. 15: Tribes; Ch. 26: Alaska).

Changes are not only happening in the oceans and along the coast. Farmers, the livestock they tend, and other outdoor laborers are expected to be adversely affected by warmer temperatures, an increasing frequency of heat waves, and an increasing number of warm nights (Ch. 10: Ag & Rural; Ch. 14: Human Health; Ch. 19: Southeast; Ch. 23: S. Great Plains). Some communities may have to adapt to both an increase in the frequency of drought and more rain falling as heavy precipitation, while deteriorating water infrastructure compounds those risks (Ch. 3: Water; Ch. 17: Complex Systems; Ch. 22: N. Great Plains; Ch. 25 Southwest). The geographic range and distribution of some pests and pathogens are projected to change in some regions, exposing livestock and crops to new or additional stressors and exposing more people to diseases transmitted by those pests (Ch. 14: Human Health; Ch. 21: Midwest).

Infrastructure across the country, which supports economic activity, is increasingly being tested and impacted by climate change, including airport runways affected by increased surface temperature and coastal streets inundated by high tide flooding (Ch. 12: Transportation). Much of the current built environment throughout the country has been developed based on the assumption that future climate will be similar to that of the past, which is no longer a valid assumption (Ch. 11: Urban). In general, the larger and faster the changes in climate, the more difficult it is for human and natural systems to adapt. Adaptation efforts not only help communities become more resilient, they may also create new jobs and help stimulate local economies (see FAQ "What are climate change mitigation, adaptation, and resilience?").

Americans Respond to the Impacts of Climate Change



Alaska

Impact
The physical and mental health of rural Alaskans is increasingly challenged by unpredictable weather and other environmental changes.

Action
The Alaska Native Tribal Health Consortium's Center for Climate and Health is using novel adaptation strategies to reduce climate-related risks including difficulty in harvesting local foods and more hazardous travel conditions.

Northern Great Plains

Impact
Flash droughts and extreme heat illustrate sustainability challenges for ranching operations, with emergent impacts on rural prosperity and mental health.

Action
The National Drought Mitigation Center is helping ranchers plan to reduce drought and heat risks to their operations.

Midwest

Impact
Increasing heavy rains are leading to more soil erosion and nutrient loss on Midwestern cropland.

Action
Iowa State developed a program for using prairie strips in farm fields to reduce soil and nutrient loss while increasing biodiversity.

Northeast

Impact
Water, energy, and transportation infrastructure are affected by snow storms, drought, heat waves, and flooding.

Action
Cities and states throughout the region are assessing their vulnerability to climate change and making investments to increase infrastructure resilience.

Northwest

Impact
Wildfire increases and associated smoke are affecting human health, water resources, timber production, fish and wildlife, and recreation.

Action
Federal forests have developed adaptation strategies for climate change that include methods to address increasing wildfire risks.

Southwest

Impact
Drought in the Colorado River basin reduced Lake Mead by over half since 2000, increasing risk of water shortages for cities, farms, and ecosystems.

Action
Seven U.S. state governments and U.S. and Mexico federal governments mobilized users to conserve water, keeping the lake above a critical level.

Southeast

Impact
Flooding in Louisiana is increasing from extreme rainfall.

Action
The Acadiana Planning Commission in Louisiana is pooling hazard reduction funds to address increasing flood risk.

Southern Great Plains

Impact
Hurricane Harvey's landfall on the Texas coast in 2017 was one of the costliest natural disasters in U.S. history.

Action
The Governor's Commission to Rebuild Texas was created to support the economic recovery and rebuilding of infrastructure in affected Texas communities.

U.S. Caribbean

Impact
Damages from the 2017 hurricanes have been compounded by the slow recovery of energy, communications, and transportation systems, impacting all social and economic sectors.

Action
The U.S. Virgin Islands Governor's Office led a workshop aimed at gathering lessons from the initial hurricane response and establishing a framework for recovery and resilience.

Hawai'i and U.S.-Affiliated Pacific Islands

Impact
The 2015 coral bleaching event resulted in an average mortality of 50% of the coral cover in western Hawai'i alone.

Action
A state working group generated management options to promote recovery and reduce threats to coral reefs.

Figure A5.22: This map shows climate-related impacts that have occurred in each region since the Third National Climate Assessment in 2014 and response actions that are helping the region address related risks and costs. These examples are illustrative; they are not indicative of which impact is most significant in each region or which response action might be most effective. Source: NCA4 Regional Chapters.

What is the social cost of carbon?

The social cost of carbon is an estimate of the monetary value of the cumulative damages caused by long-term climate change due to an additional amount of carbon dioxide (CO_2) emitted. This value quantifies the potential benefits of a reduction in CO_2 emissions.

The social cost of carbon (SCC) includes the economic costs of climate change that will be felt in market sectors such as agriculture, energy services, and coastal resources, as well as nonmarket impacts on human health and ecosystems, to name a few.[26] SCC values are computed by simulating the "causal chain" from greenhouse gas emissions to physical climate change to climate damages in order to estimate the additional damages over time incurred from an additional metric ton of CO_2.[27] This value can be used to inform climate risk management decisions at national, state, and corporate levels, as well as in regulatory impact analysis to evaluate benefits of marginal CO_2 reductions—for example, in rules affecting appliance efficiency, power generation, industry, and transportation, such as the benefits of increased vehicle gas mileage standards. As with many complex, interacting systems, it is challenging to develop comprehensive SCC estimates, but this is an active area of research guided by recent recommendations from the National Academies of Sciences, Engineering, and Medicine to keep up with the current state of scientific knowledge, better characterize key uncertainties, and improve transparency.[28] Notably, estimating the SCC depends on normative social values such as time preference, risk aversion, and equity considerations that can lead to a range of values. Ongoing interdisciplinary collaborations and research findings from the climate change impacts, adaptation, and vulnerability literature—including those discussed in the Fourth National Climate Assessment—are being used to improve the robustness of climate damage quantification and, thus, SCC estimates.

What are climate change mitigation, adaptation, and resilience?

"Mitigation," "adaptation," and "resilience" are related but different terms in the context of climate change. Mitigation refers to actions that reduce the amount and speed of future climate change by reducing emissions of greenhouse gases (GHGs)or removing carbon dioxide from the atmosphere. Adaptation refers to adjustments in natural or human systems in response to a new or changing environment that exploit beneficial opportunities or moderate negative effects. Thus, adaptation is closely related to resilience, which is the capacity to prevent, withstand, respond to, and recover from a disruption with minimum damage to social well-being, the economy, and the environment.

Mitigation efforts can reduce emissions or increase storage of GHGs. For example, shifting from fossil fuels to low-carbon energy sources will generally result in the reduction of GHG emissions into the atmosphere. Mass transit, energy-efficient buildings, and electric vehicles can be used instead of high-emission alternatives. Land-use changes that increase the amount of carbon stored in soil and biomass, as well as some geoengineering techniques, constitute mitigation efforts that take carbon dioxide (CO_2) out of the atmosphere (see FAQ "Can geoengineering be used to remove carbon dioxide from the atmosphere or otherwise reverse global warming?") (see also Ch. 29: Mitigation).

Adaptation involves policies, strategies, and technologies designed to reduce the risk of harm from climate-related impacts. Some adaptation actions are technical engineering solutions designed to address specific impacts, such as building a seawall in the face of sea level rise or breeding new crops that do well in the context of drought. Other adaptation actions involve decision-making processes, policies, or approaches that bring people together to support coordinated action (Ch. 28: Adaptation). Adaptation often involves incremental adjustments to current systems, but larger transformations may be necessary, especially as some systems cross thresholds or tipping points.

Adaptation and mitigation actions can be undertaken simultaneously to reduce concentrations of GHGs in the atmosphere while also reducing the risk of climate-related impacts. Both adaptation and mitigation can have co-benefits—societal benefits that are not necessarily related to climate change (Ch. 29: Mitigation). For example, a new coastal restoration project to plant a mangrove forest will remove CO_2 from the atmosphere while providing valuable ecosystem services—a buffer against storm surges, reduced erosion, habitat for wildlife, and filtration of human pollutants (Ch. 8: Coastal).

Climate resilience refers to the capacity of a human or natural system to respond to and recover from climate-related hazards, such as droughts or floods, in ways that maintain their essential or valued identity, functions, and structure. Resilient systems respond to climate stressors or impacts with less harm while also improving their ability to absorb future impacts and maintaining capacity for adaptation and learning. A resilient rural community might have the capacity to share knowledge and resources to help farmers deal with droughts while improving their ability to absorb future impacts by building long-term structures to conserve water resources (Ch. 24: Northwest). Resilience can be bolstered by diversity (such as species diversity or employment diversity), redundancy (the ability for one part of the system to take over essential functions if another is damaged), social networks, knowledge sharing, and good governance (Ch. 7: Ecosystems).

Is timing important for climate mitigation?

Yes. The choices made today largely determine what impacts may occur in the future. Carbon dioxide can persist in the atmosphere for a century or more, so emissions released now will still be affecting climate for years to come. The sooner greenhouse gas (GHGs) emissions are reduced, the easier it may be to limit the long-term costs and damages due to climate change. Waiting to begin reducing emissions is likely to increase the damages from climate-related extreme events (such as heat waves, droughts, wildfires, flash floods, and stronger storm surges due to higher sea levels and more powerful hurricanes).

The effect of increasing atmospheric concentrations of carbon dioxide (CO_2) and other GHGs on the climate system can take decades to be fully realized. The resulting change in climate and the impacts of those changes can then persist for centuries. The longer these changes in climate continue, the greater the resulting impacts; some systems may not be able to adapt if the change is too much or too fast.

The long-term equilibrium temperature from GHG emissions will be a function of cumulative emissions over time, not the specific year-to-year emissions. Thus, staying within a specific warming target will depend on the total net emissions (including increases in carbon uptake) over a given future period.

However, the timing and nature of changes are important in both reducing short-term warming and meeting any particular long-term warming limit. Long-term reductions in the rate and magnitude of global warming can be made by reducing total emissions of CO_2. Near-term reductions in the rate of climate change can be made by reducing human-caused emissions of short-lived but highly potent GHGs such as methane and hydrofluorocarbons. These pollutants remain in the atmosphere from weeks to about a decade—much shorter than CO_2—but have a much greater warming influence than CO_2 (Figure A5.23).[17]

Benefit of Earlier Action to Reduce Emissions

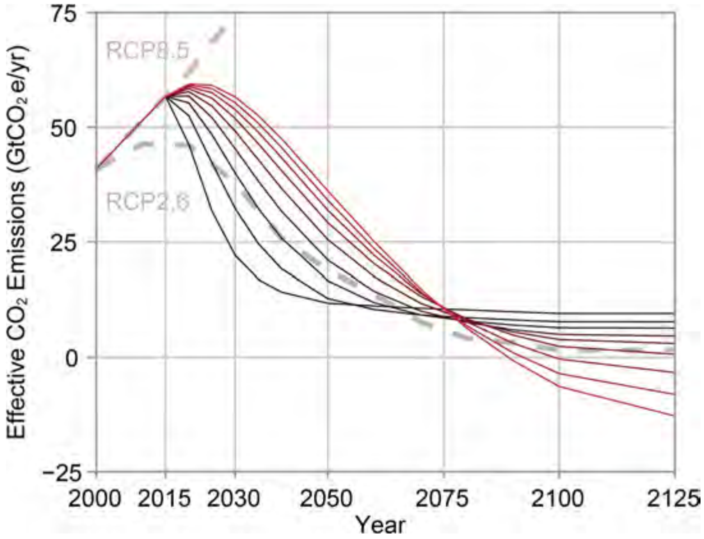


Figure A5.23: This figure shows possible future pathways for global annual emissions of GHGs for which the global mean temperature would likely (66%) not exceed 3.6°F (2°C) above the preindustrial average. The black curves on the bottom show the fastest reduction in emissions, with rapid near-term mitigation and little to no negative emissions required in the future. The red curves on top show slower rates of mitigation, with slow near-term reductions in emissions and large negative emission requirements in the future. Here, the annual global GHG emissions are in units of gigatons of CO_2 equivalent, a measurement that expresses the warming impact of all GHGs in terms of the equivalent amount of CO_2. Source: adapted from Sanderson et al. 2016.[29]

Are there benefits to climate change?

While some climate changes currently have beneficial effects for specific sectors or regions, many studies have concluded that climate change will generally bring more negative effects than positive ones in the future. For example, current benefits of warming include longer growing seasons for agriculture, more carbon dioxide for plants, and longer ice-free periods for shipping on the Great Lakes. However, longer growing seasons, along with higher temperatures and increased carbon dioxide levels, can increase pollen production, intensifying and lengthening the allergy season. Longer ice-free periods on the Great Lakes can result in more lake-effect snowfalls.

Many analyses of this question have concluded that climate change will, on balance, bring more negative effects than positive ones in the future. This is largely because our society and infrastructure have been built for the climate of the past, and changes from those historical climate conditions impose costs and management challenges (Ch. 11: Urban). For example, while longer warm seasons may provide a temporary economic boon to coastal communities reliant on tourism, many of these same areas are vulnerable not only to sea level rise but also to risks from ocean acidification and warmer waters that can impact the ecosystems (such as coral reefs) that bring people to the coasts (Ch. 8: Coastal). As another example, while some studies have shown that certain crops in certain regions may benefit from additional carbon dioxide (CO_2) in the atmosphere (sometimes referred to as the CO_2 fertilization effect), these potential gains are expected to be offset by crop stress caused by higher temperatures, worsening air quality, and strained water availability (see FAQ "How do higher carbon dioxide concentrations affect plant communities and crops?") (see also Ch. 10: Ag & Rural). Furthermore, any accrued benefits are likely to be short-lived and depreciate significantly as warming continues through the century and beyond.

Are some people more vulnerable to climate change than others?

Yes. Climate change affects certain people and populations differently than others. Some communities have higher exposure and sensitivity to climate-related hazards than others. Some communities have more resources to prepare for and respond to rapid change than others. Communities that have fewer resources, are underrepresented in government, live in or near deteriorating infrastructure (such as damaged levees), or lack financial safety nets are all more vulnerable to the impacts of climate change.

Vulnerability here refers to the degree to which physical, biological, and socioeconomic systems are susceptible to and unable to cope with adverse impacts of climate change. Vulnerability encompasses sensitivity, adaptive capacity, exposure, and potential impacts. For example, older people living in cities with no air conditioning have less adaptive capacity and increased sensitivity and vulnerability to heat stress during extreme heat events (Ch. 14: Human Health). Communities that live on atolls in the Marshall Islands have high exposure and are acutely at risk to sea level rise and saltwater intrusion due to the low land height and small land area (Ch. 27: Hawai‘i & Pacific Islands). A history of neglect, political or otherwise, in a given neighborhood can result in dilapidated infrastructure, which in turn can lead to situations such as levee failures, making whole communities vulnerable to flooding and other potential impacts (Ch. 14: Human Health). Poverty can make evacuation during storm events challenging and can make rebuilding or relocating harder following an extreme event. In some Indigenous communities, lack of water and sanitation systems can put people at risk during drought (Ch. 15: Tribes). Additionally, some subpopulations are already more affected by environmental exposures, such as air pollution or extreme heat. If communities or individuals experience a combination of these vulnerability factors, they are at even greater risk. Vulnerable communities and individuals face these disparities today and will likely face increased challenges in the future under a changing climate.

How will climate change impact economic productivity?

Many impacts of climate change are expected to have negative effects on economic productivity, such as increased prices of goods and services. For example, increased exposure to extreme heat may reduce the hours some individuals are able to work. Physical capital—such as food, equipment, and property—that is derived from the production of goods and services may be impacted because of lower production and higher costs as a result of climate change. Sea level rise, stronger storm surges, and increased heavy downpours that cause flooding can disrupt supply chains or damage properties, structures, and infrastructure that form the backbone of the Nation's economy.

High temperatures and storm intensity, which are both linked to more deaths and illness, are projected to increase due to climate change, which would in turn increase health care costs for medical treatment. At the same time, these health effects directly impact labor markets. Workers in industries with the greatest exposure to weather extremes may decrease the amount of time they spend at work, while workers across a wide range of sectors may find their productivity impaired while on the job (Ch. 14: Human Health). These labor market impacts translate into lower earnings for workers and firms.[30,31]

Climate change is likely to affect physical capital that serves as an important input to economic production. In farming, where weather is a key determinant of agricultural yield, increasing temperatures and drought may lead to net decreases in the amount of food that farms produce (Ch.10: Ag & Rural).[32] Extreme heat can also cause manufacturing equipment to break down with greater frequency, while rising sea levels and increased storm intensity can destroy equipment and property across all types of economic activities along American coastlines.[30,33]

In addition to damaging private property, increased weather extremes can destroy vital public infrastructure, such as roads, bridges, and ports. Since this infrastructure is an integral part of supply chains that drive the American economy, a disruption in their accessibility—or even their destruction—can have large impacts on corporate profits, while their repairs require a diversion of resources away from other useful government projects or an increase in taxes to finance reconstruction (Ch. 11: Urban).[34,35]

Can we slow climate change?

Yes. While we cannot stop climate change overnight, or even over the next several decades, we can limit the amount of climate change by reducing human-caused emissions of greenhouse gases (GHGs). Even if all human-related emissions of carbon dioxide and other GHGs were to stop today, Earth's temperature would continue to rise for a number of decades and then slowly begin to decline. Ultimately, warming could be reversed by reducing the amount of GHGs in the atmosphere. The challenge in slowing or reversing climate change is finding a way to make these changes on a global scale that is technically, economically, socially, and politically viable.

The most direct way to significantly reduce the magnitude of future climate change is to reduce the global emissions of GHGs. Emissions can be reduced in many ways, and increasing the efficiency of energy use is an important component of many potential strategies (Ch. 29: Mitigation). For example, because the transportation sector accounts for about 29% of the energy used in the United States, developing and driving more efficient vehicles and changing to fuels that do not contribute significantly to GHG emissions over their lifetimes would result in fewer emissions per mile driven. A large amount of energy in the United States is also used to heat and cool buildings, so changes in building design could dramatically reduce energy use (Ch 29: Mitigation). While there is no single approach that will solve all the challenges posed by climate change, there are many options that can reduce emissions and help prevent some of the potentially serious impacts of climate change (Figure A5.24).[17]

Pathways to Carbon Emissions Reduction

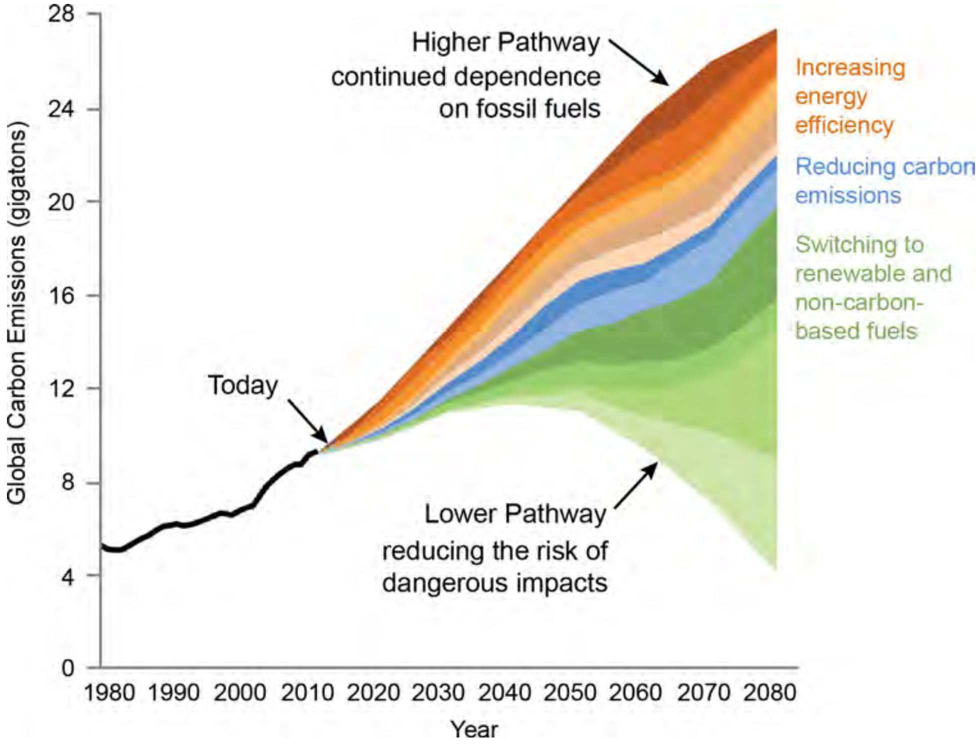


Figure A5.24: Reducing carbon emissions from a higher scenario (RCP8.5) to a lower scenario (RCP4.5) can be accomplished with a combination of many technologies and policies. In this example, these emissions reduction "wedges" could include increasing the energy efficiency of appliances, vehicles, buildings, electronics, and electricity generation (orange wedges); reducing carbon emissions from fossil fuels by switching to lower-carbon fuels or capturing and storing carbon (blue wedges); and switching to renewable and non-carbon-emitting sources of energy, including solar, wind, wave, biomass, tidal, and geothermal (green wedges). The shapes and sizes of the wedges shown here are illustrative only. Source: adapted from Walsh et al. 2014.[6]

Can geoengineering be used to remove carbon dioxide from the atmosphere or otherwise reverse global warming?

In theory, it may be possible to reverse some aspects of global warming through technological interventions called geoengineering, which can complement mitigation and adaptation. But many questions remain. Geoengineering approaches generally fall under two categories: 1) carbon dioxide removal and 2) reducing the amount of the sun's energy that reaches Earth's surface. Due to uncertain costs and risks of some geoengineering approaches, more traditional mitigation actions to reduce emissions of greenhouse gases (GHGs) are generally viewed as more feasible for avoiding the worst impacts from climate change currently. However, targeted studies to determine the feasibility, costs, risks, and benefits of various geoengineering techniques could help clarify the impacts.

Removal of carbon dioxide (CO_2) from the atmosphere could be undertaken by applying land management methods that increase carbon storage in forests, soils, wetlands, and other terrestrial or aquatic carbon reservoirs. Trees and plants draw down CO_2 from the atmosphere during photosynthesis and store it in plant structures. Reforesting large tracts of deforested lands would help reduce atmospheric concentrations of CO_2. New technologies could also be used to capture CO_2 either directly from the atmosphere or at the point where it is produced (such as at coal-fired power plants) and store it underground. However, CO_2 removal may be costly and has long implementation times, and the removal of CO_2 from the atmosphere must be essentially permanent if climate impacts are to be avoided.[17,36]

Solar radiation management (SRM) is an intentional effort to reduce the amount of sunlight that reaches Earth's surface by increasing the amount of sunlight reflected back to space. Since SRM does not reverse the increased concentrations of CO_2 and other GHGs in the atmosphere, this approach does not address direct impacts from elevated $CO_{2,}$ such as damage to marine ecosystems from increasing ocean acidification.[17,37] Instead, it introduces another human influence on the climate system that partially cancels some of the effects of increased GHGs in the atmosphere. SRM methods include making clouds brighter and more reflective, injecting reflective aerosol particles into the upper or lower atmosphere, or increasing the reflectivity of Earth's surface. SRM can work in conjunction with CO_2 removal and other mitigation efforts and can be phased out over time. Yet this method would require sustained costs, has not been well studied, and could have harmful unintended consequences, such as stratospheric ozone depletion.[38]

Ecological Effects

What causes global sea level rise, and how will it affect coastal areas in the coming century?

Global sea level is rising, primarily in response to two factors: 1) thermal expansion of ocean waters and 2) melting of land-based ice, both due to climate change. Thermal expansion refers to the physical expansion (or increase in volume) of water as it warms. Melting of mountain glaciers and the Antarctic and Greenland ice sheets contributes additional water to the oceans, thereby raising global average sea level. Global average sea level has risen 7–8 inches since 1880, and about 3 inches of that has occurred since 1993. Sea level rise will increasingly contribute to high tide flooding and intensify coastal erosion over the coming century.

At any given location, the situation is more complicated because other factors come into play. For example, coastlands are rising in some places and sinking in others due to both natural causes (such as tectonic shifts) and human activities (such as groundwater or hydrocarbon extraction). Where coastlands are rising as fast as (or faster than) sea level, relative local sea level may be unchanged (or decreasing). Where coastlands are sinking (called subsidence), relative local sea level may be rising faster than the global average (Figure A5.25) (see also Ch. 23: S. Great Plains). Other variables can influence relative sea level locally, including natural climate variability patterns (for example, El Niño/La Niña events) and regional shifts in wind and ocean current patterns.[39]

Global sea level rise is already affecting the U.S. coast in many locations (Ch. 8: Coastal). High tide flooding with little or no storm effects (also referred to as nuisance, sunny-day, or recurrent flooding), coastal erosion, and beach and wetland loss are all increasingly common due to decades of local relative sea level rise (Ch. 19: Southeast).[39] Sea level is expected to continue rising at an accelerating rate this century under either a lower or higher scenario (RCP4.5 or RCP8.5), increasing the frequency of high tide flooding, intensifying coastal erosion and beach and wetland loss, and causing greater damage to coastal properties and structures due to stronger storm surges (Ch. 18: Northeast; Ch. 8: Coastal). Relative local sea level rise projections can be visualized at https://coast.noaa.gov/digitalcoast/tools/slr.html.

Relative Sea Level Projected to Rise Along Most U.S. Coasts

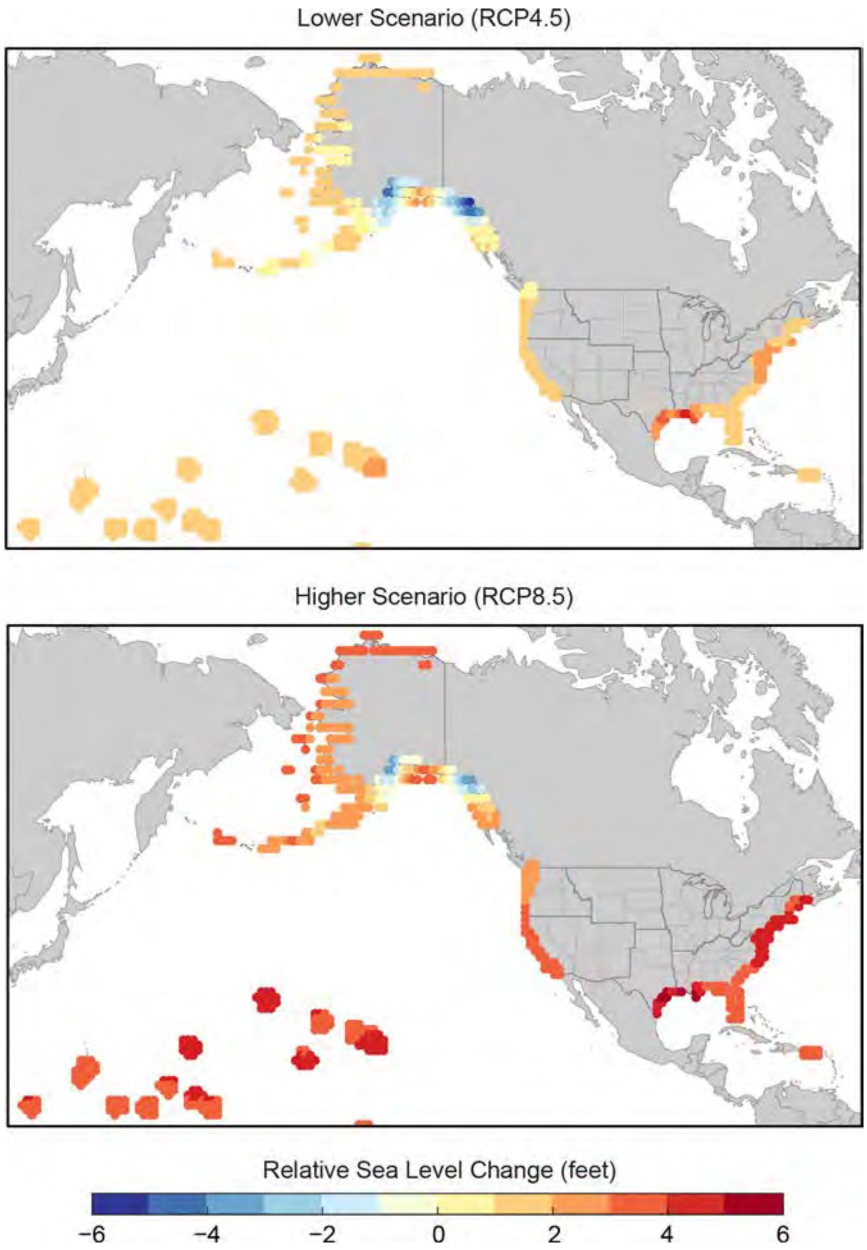


Figure A5.25: The maps show projections of change in relative sea level along the U.S. coast by 2100 (as compared to 2000) under the lower and higher scenarios (RCP4.5 and RCP8.5, top and bottom panels, respectively).[39] Globally, sea levels will continue to rise from thermal expansion of the ocean and melting of land-based ice masses (such as Greenland, Antarctica, and mountain glaciers). Regionally, however, the amount of sea level rise will not be the same everywhere. Where land is sinking (as along the Gulf of Mexico coastline), relative sea level rise will be higher, and where land is rising (as in parts of Alaska), relative sea level rise will be lower. Changes in ocean circulation (such as the Gulf Stream) and gravity effects due to land ice melt will also alter the heights of the ocean regionally. Sea levels are expected to continue to rise along almost all U.S. coastlines, and by 2100, under the higher scenario, coastal flood heights that today cause major damages to infrastructure would become common during high tides nationwide. Source: adapted from Sweet et al. 2017.[40]

How does global warming affect arctic sea ice cover?

The Arctic region has warmed by about 3.6°F since 1900—double the rate of the global temperature increase. Consequently, sea ice cover has declined significantly over the last four decades. In the summer and fall, sea ice area has dropped by 40% and sea ice volume has dropped 70% relative to the 1970s and earlier. Decline in sea ice cover plays an important role in arctic ecosystems, ultimately impacting Alaska residents.

Arctic sea ice today is in the most reduced state since satellite measurements began in the late 1970s, and the current rate of sea ice loss is also unprecedented in the observational record (Figures A5.26 and A5.27) (see also Ch. 2: Climate). Arctic sea ice cover is sensitive to climate change because strong self-reinforcing cycles (positive feedbacks) are at play. As sea ice melts, more open ocean is exposed. Open ocean (a dark surface) absorbs much more sunlight than sea ice (a reflective white surface). That extra absorbed sunlight leads to more warming locally, which in turn melts more sea ice, creating a positive feedback (Ch. 2: Climate). Annual average arctic sea ice extent has decreased between 3.5% and 4.1% per decade since the early 1980s, has become thinner by 4.3 to 7.5 feet, and has started melting earlier in the year. September sea ice extent, when the arctic sea ice is at a minimum, has decreased by 10.7% to 15.9% per decade since the 1980s. Scientists project sea ice-free summers in the Arctic by the 2040s (Figure A5.27) (see Ch. 26: Alaska).[2]

Arctic sea ice plays a vital role in arctic ecosystems. Changes in the extent, duration, and thickness of sea ice, along with increasing ocean temperature and ocean acidity, alter the distribution of Alaska fisheries and the location of polar bears and walruses, all of which are important resources for Alaska residents, particularly coastal Native Alaska communities (Ch. 26: Alaska). Winter sea ice may keep forming in a warmer world, but it could be much reduced compared to the present (see Taylor et al. 2017[2] for more details).

Annual Minimum Sea Ice Extent Decreasing

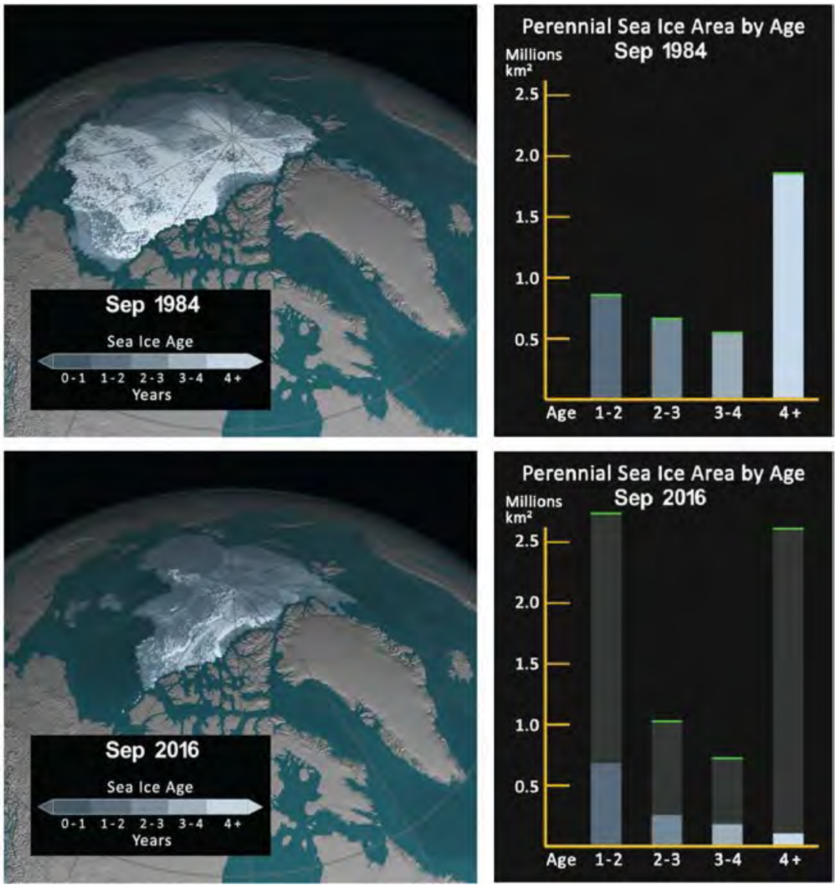


Figure A5.26: Both the extent and the age of the September sea ice cover are shown for 1984 (top) and 2016 (bottom). The colors of the bars on the right panels correspond to the colors used to indicate the age of the sea ice in the panels on the left. The green bars on the graphs on the right mark the maximum extent for each age range during the record. The year 1984 is representative of September sea ice characteristics during the 1980s. Over time, September sea ice extent and the amount of multiyear ice have greatly decreased. The years 1984 and 2016 are selected as endpoints in the timeseries. A movie of the complete time series is available at http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489. Source: adapted from NASA 2016.[41]

Decreasing Arctic Sea Ice Extent

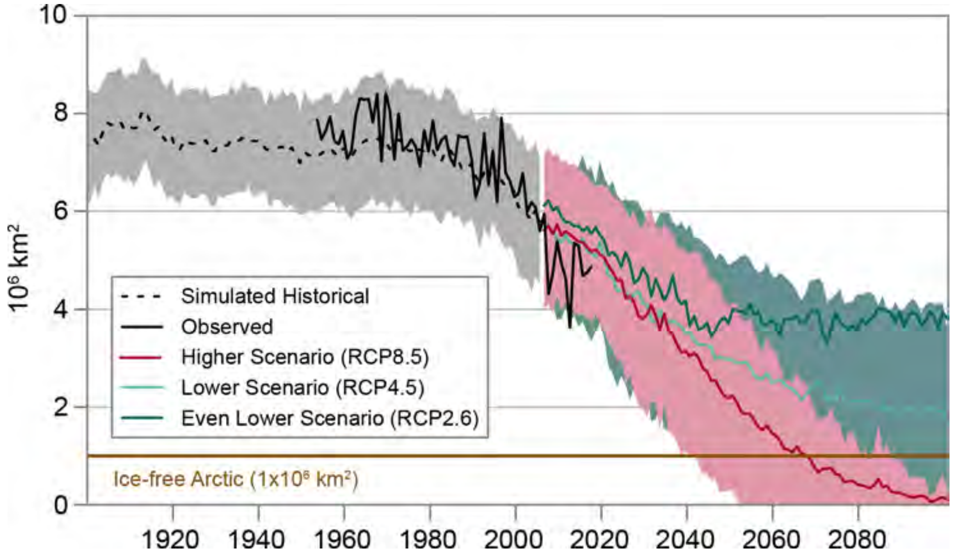


Figure A5.27: This graph shows historical simulations of arctic sea ice extent starting in 1900 (dotted black line), observations of arctic sea ice extent (solid black line), and future projections of arctic sea ice extent (colored lines) from 2005 through 2100 under three RCP scenarios. The projections shown are the average values from a set of climate model simulations, and the shaded pink and green regions indicate one-standard-deviation confidence intervals around the average values for the higher and lower scenarios, respectively. Source: adapted from Stroeve and Notz 2015.[42] ©2015 Elsevier B.V. All rights reserved.

Is Antarctica losing ice? What about Greenland?

Yes. Overall, the ice sheets on both Greenland and Antarctica, the largest areas of land-based ice on the planet, are losing ice as the atmosphere and oceans warm. This ice loss is important both as evidence that the planet is warming and because it contributes to rising sea levels.

The Antarctic ice sheet is up to three miles deep and contains enough water to raise sea level about 200 feet. Because Antarctica is so cold, there is little melting of the ice sheet, even in summer. However, the ice flows towards the ocean where above-freezing ocean water speeds up the melting process, which breaks the ice into free-floating icebergs (a process called calving). Melting, calving, and the flow of ice into the oceans around Antarctica—especially on the Antarctic Peninsula—have all accelerated in recent decades, and the result is that Antarctica is losing about 100 billion tons of ice per year (contributing about 0.01 inch per year to sea level rise; Figure A5.28).[39] While there has been slight growth in some parts of the Antarctic ice sheet, the gain is more than offset by ice mass loss elsewhere, especially in West Antarctica and along the Antarctic Peninsula. The West Antarctic ice sheet, which contains enough ice to raise global sea level by 10 feet, is likely to lose ice much more quickly if its ice shelves disintegrate. Additionally, warming oceans under the ice sheet are melting the areas where ice sheets go afloat in West Antarctica, exacerbating the risk of more rapid melt in the future.

Greenland contains only about one-tenth as much ice as the Antarctic ice sheet, but if Greenland's ice sheet were to entirely melt, global sea level would still rise about 20 feet. (For additional information on the impacts of sea level rise on the United States directly, see Ch. 8: Coastal; Ch. 18: Northeast; Ch. 19: Southeast; and Ch. 20: U.S. Caribbean.) Annual surface temperatures in Greenland are warmer than Antarctica, so melting occurs over large parts of the surface of Greenland's ice sheet each summer. Greenland's melt area has increased over the past several decades (Figure A5.28). The Greenland ice sheet is presently thinning at the edges (especially in the south) and slowly thickening in the interior, increasing the steepness of the ice sheet, which has sped up the flow of ice into the ocean over the past decade. This trend will likely continue as the surrounding ocean warms. Greenland's ice loss has increased substantially in the past decade, losing ice at an average rate of about 269 billion tons per year from April 2012 to April 2016 (contributing over 0.02 inch per year to sea level rise).[4]

Greenland and Antarctica Are Losing Ice

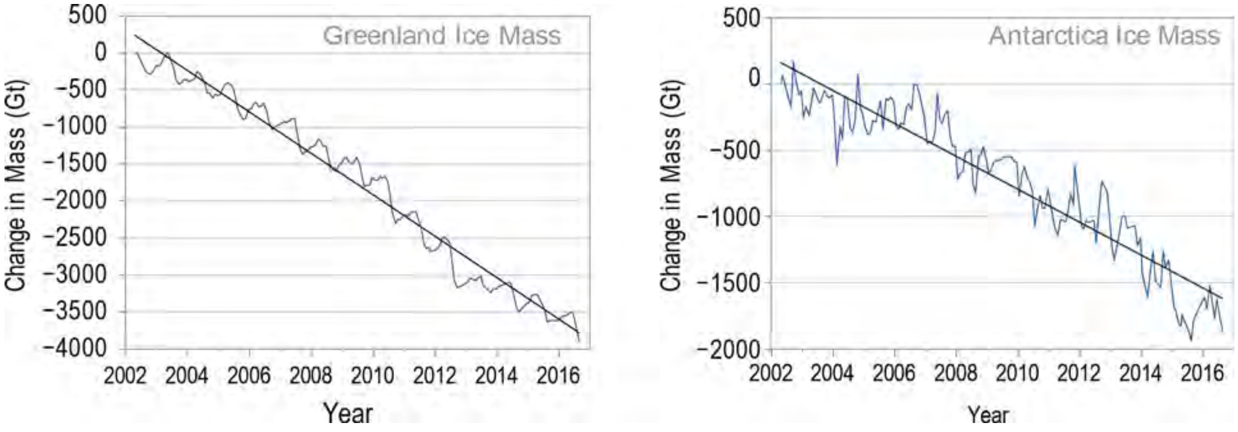


Figure A5.28: The graphs show satellite measurements of the change in ice mass for the two polar ice sheets through August 2016 as compared to April 2002. Both the Greenland and Antarctic ice sheets are losing ice as the atmosphere and oceans warm. Source: adapted from Wouters et al. 2013.[43] Reprinted by permission from Macmillan Publishers Ltd., ©2013.

How does climate change affect mountain glaciers?

Glacier retreat is one of the most important lines of evidence for global warming. Around the world, glaciers in most mountain ranges are receding at unprecedented rates. Many glaciers have disappeared altogether this century, and many more are expected to vanish within a matter of decades. Glaciers will still be around within the next century, but they will be more isolated, closer to the poles, and at higher elevations.

Glaciers are critical freshwater reservoirs that slowly release water over warmer months, which helps sustain freshwater streamflows that provide drinking and irrigation water, as well as hydropower to downstream communities. However, increasing temperatures and decreasing amounts of precipitation falling as snow are major drivers of glacial retreat (see Ch. 2: Climate; Ch. 22: N. Great Plains; Ch. 24: Northwest; Ch. 26: Alaska). Glaciers retreat when melting and evaporation outpace the accumulation of new snow. Slope, altitude, ice flow, location, and volume also contribute to the speed and extent of glacial retreat, which complicates the relationship between increasing temperature and glacial melt. Due to these local factors, not all glaciers globally are retreating. For example, melting may slow as the glaciers retreat to the upper slopes, under headwalls and steep cliffs, and into more shaded areas.

In recent decades, the mountains of Glacier National Park (GNP) in Montana have experienced an increase in summer temperatures and a reduction in the winter snowpack that forms the mountain glaciers. The annual average temperature in GNP has increased by 2.4°F since 1900, spring and summer minimum temperatures have risen, and the percentage of precipitation that comes as rain rather than snow has increased.[44,45,46] Mountain snowpacks now hold less water than they used to and have begun to melt at least two weeks earlier in the spring. This earlier melting alters glacier stability, as well as downstream water supplies, with implications for wildlife, agriculture, and fire management.

In a recent study, scientists looked at 39 glaciers in and around GNP and compared aerial photos and digital maps from 1966 to 2016. Currently, only 26 glaciers are bigger than 25 acres, the minimum size used for defining a glacier. When GNP was established early in 1910, it is estimated that there were 150 glaciers larger than 25 acres. Long-term studies of glacier size have shown that the rate of melting has fluctuated in response to decade-long climate cycles and that the melting rate has risen steeply since about 1980.[47,48] Over the next 30 years, glaciologists project that most glaciers in GNP will melt to a point where they are too small to be active glaciers, and some may disappear completely. All glaciers in the park are under severe threat of completely melting by the end of the century.[4]

How are the oceans affected by climate change?

The oceans have absorbed over 90% of the excess heat energy and more than 25% of the carbon dioxide (CO_2) that is trapped in the atmosphere as a result of human-produced greenhouse gases (GHGs). Due to this increase in GHGs in the atmosphere, all ocean basins are warming and experiencing changes in their circulation and seawater chemistry, all of which alter ecosystem structure and marine biodiversity.

The world's oceans have been and will continue to be impacted by climate change. More than 50% of the world's marine ecosystems are already exposed to conditions (temperature, oxygen, salinity, and pH) that are outside the normal range of natural climate variability, and this percentage will rise as the planet warms (Ch. 9: Oceans).[1] Global warming will alter the ability of species to survive and can reorganize ecosystems, creating novel habitats and/or reducing biodiversity. Some species are responding to increased ocean temperatures by shifting their geographic ranges, generally to higher latitudes, or altering the timing of life stages (for example, spawning; Figure A5.29) (see Ch. 7: Ecosystems; Ch. 18: Northeast).[49] Other species are unable to adapt as their habitats deteriorate (for example, due to loss of sea ice) or the rate of climate-related changes occurs faster than they can move (for example, in the case of sessile organisms, such as oysters and corals).

Physical changes to the ocean system will also occur. Observations and projections suggest that in the next 100 years, the Gulf Stream (part of the larger "ocean conveyor belt") could slow down as a result of climate change, which could increase regional sea level rise and alter weather patterns along the U.S. East Coast.[13,50]

In addition to causing changes in temperature, precipitation, and circulation, increasing atmospheric levels of CO_2 have a direct effect on ocean chemistry. The oceans currently absorb about a quarter of the 10 billion tons of CO_2 emitted to the atmosphere by human activities every year. Dissolved CO_2 reacts with seawater to make it more acidic. This acidification impacts marine life such as shellfish and corals, making it more difficult for these calcifying animals to make their hard external structures (Ch. 8: Oceans; Ch. 24: Northwest).

Over the last 50 years, inland seas, estuaries, and coastal and open oceans have all experienced major oxygen losses. A warmer ocean holds less oxygen. Warming also changes the physical mixing of ocean waters (for example, upwelling and circulation) and can interact with other human-induced changes. For example, fertilizer runoff entering the Gulf of Mexico through the Mississippi River can stimulate harmful algal blooms. These blooms eventually decay, creating large "dead zones" of water with very low oxygen, where animals cannot survive. Warmer conditions slow down the rate at which this oxygen can be replaced, exacerbating the impact of the dead zone. These are just a few of the changes projected to occur, as detailed in Chapter 9: Oceans.

Projected Changes in Maximum Fish Catch Potential

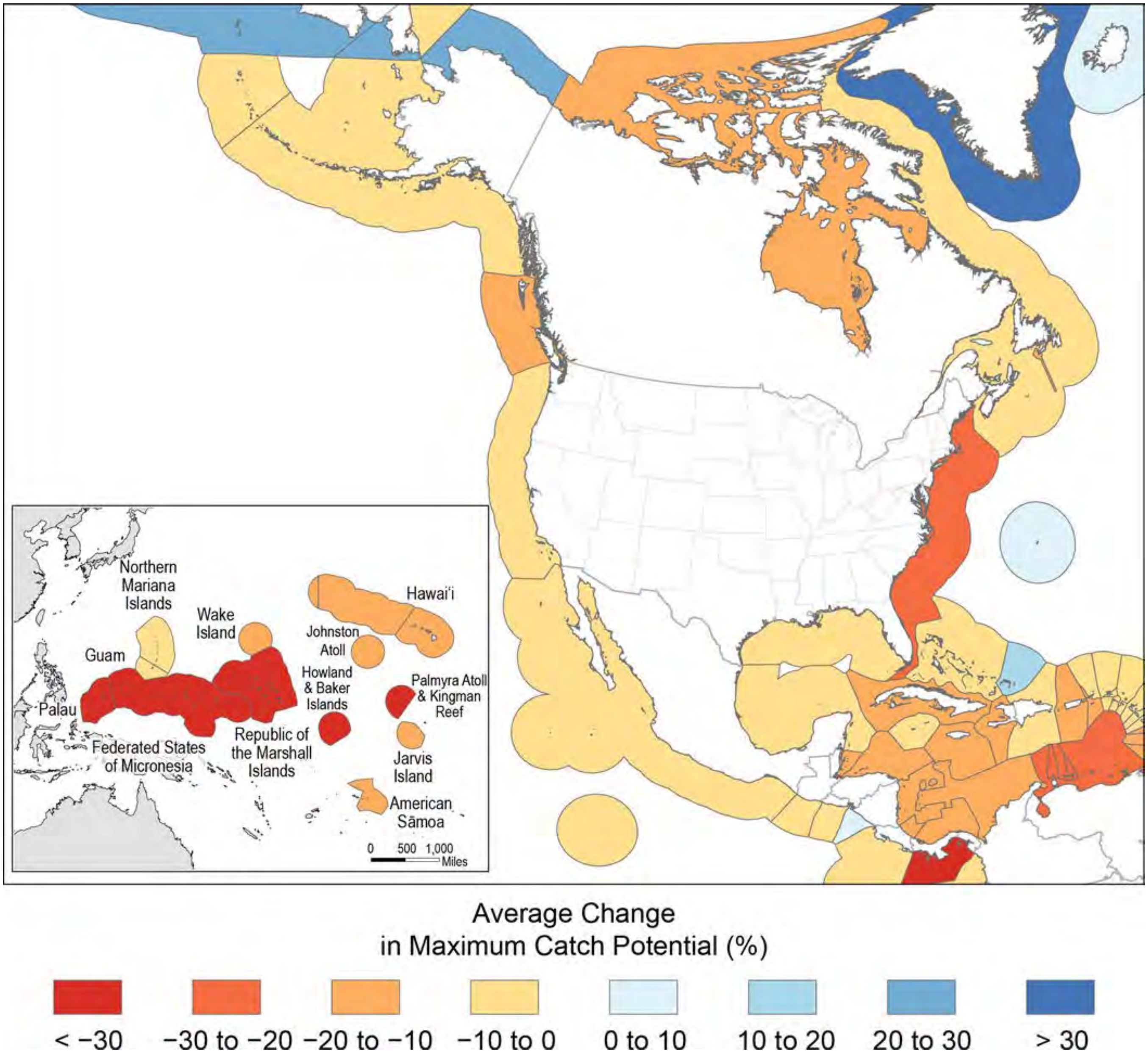


Figure A5.29: The figure shows average projected changes in fishery catches within large marine ecosystems for 2041–2060 relative to 1991–2010 under a higher scenario (RCP8.5). All U.S. large marine ecosystems, with the exception of the Alaska Arctic, are expected to see declining fishery catches. Source: adapted from Lam et al. 2016.[51]

What is ocean acidification, and how does it affect marine life?

The oceans currently absorb more than a quarter of the 10 billion tons of carbon dioxide (CO_2) released annually into the atmosphere from human activities. CO_2 reacts with seawater to form carbonic acid, so more dissolved CO_2 increases the acidity of ocean waters. When seawater reaches a certain acidity, it eats away at, or corrodes, the shells and skeletons made by shellfish, corals, and other species—or impedes the ability of organisms to grow them in the first place.

Since the beginning of the Industrial Revolution, the acidity of surface ocean waters has increased approximately 30%. The oceans will continue to absorb CO_2 produced by human activities, causing acidity to rise further (Figure A5.30). Ocean waters are not acidifying at the same rate around the globe, largely due to differences in ocean temperature. Warmer, low-latitude waters naturally hold less CO_2 and therefore tend to be less acidic. Colder, high-latitude waters naturally hold more CO_2, have increased acidity, and are closer to the threshold where shells and skeletons tend to corrode. Coastal and estuarine waters are also acidified by local phenomena, such as freshwater runoff from land, nutrient pollution, and upwelling.[1]

In the past five years, scientists have found that the shells of small planktonic snails (called pteropods) are already partially dissolved in locations where ocean acidification has made ocean waters corrosive, such as in the Pacific Northwest and near Antarctica. Pteropods are an important food source for Pacific salmon, so impacts to pteropods could cause changes up the food chain. Acidification has also affected commercial oyster hatcheries in the Pacific Northwest, where acidified waters impaired the growth and survival of oyster larvae (Ch. 24: Northwest).

Because marine species vary in their sensitivity to ocean acidification, scientists expect some species to decline and others to increase in abundance in response to this environmental change. Relative changes in species performance can ripple through the food web, reorganizing ecosystems as the balance between predators and prey shifts and habitat-forming species increase or decline. Habitat-forming species, such as corals and oysters, that grow by using minerals from the seawater to build mass are particularly vulnerable. It is difficult to predict exactly how ocean acidification will change ecosystems. Scientists and managers are now using computer models to project potential consequences to fisheries, protected species, and habitats (see Ch. 9: Oceans for more details).

Projected Change in Surface Ocean Acidity

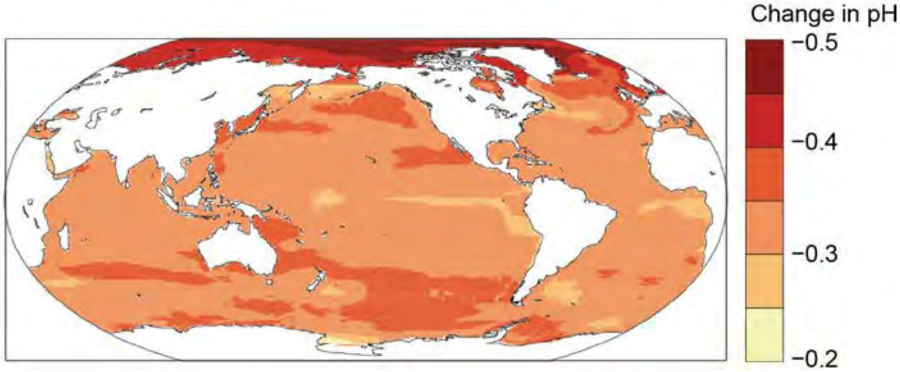


Figure A5.30: This figure shows projected changes in sea surface pH in 2090–2099 relative to 1990–1999 under the higher scenario (RCP8.5). As shown in the figure, every ocean is expected to increase in acidity, with increases in the Arctic Ocean projected to become the most pronounced. Source: adapted from Bopp et al. 2013 (CC BY 3.0).[52]

How do higher carbon dioxide concentrations affect plant communities and crops?

Plant communities and crops respond to higher atmospheric carbon dioxide concentrations in multiple ways. Some plant species are more responsive to changes in carbon dioxide than others, which makes projecting changes difficult at the plant community level. For approximately 95% of all plant species, an increase in carbon dioxide represents an increase in a necessary resource and could stimulate growth, assuming other factors like water and nutrients are not limiting and temperatures remain in a suitable growing range.

Along with water, nutrients, and sunlight, carbon dioxide (CO_2) is one of four resources necessary for plants to grow. At the level of a single plant, all else being equal, an increase in CO_2 will tend to accelerate growth because of accelerated photosynthesis, but a plant's ability to respond to increased CO_2 may be limited by soil nutrients. Exactly how much growth stimulation will occur varies significantly from species to species. However, the interaction between plants and their surrounding environment complicates the relationship. As CO_2 increases, some species may respond to a higher degree and become more competitive, which may lead to changes in plant community composition. For example, loblolly pine and poison ivy both grow in response to elevated CO_2; however, poison ivy responds more and becomes more competitive.[53]

The expected effects of increased CO_2 in agricultural plants are in line with these same patterns. Some crops that are not experiencing stresses from nutrients, water, or biotic stresses such as pests and disease are expected to benefit from CO_2 increases in terms of growth. However, the quality of those crops can suffer, as rising levels of atmospheric CO_2 can decrease dietary iron and other micronutrients (Ch. 14: Human Health). Plants often become less water stressed as CO_2 levels increase, because high atmospheric CO_2 allows plants to photosynthesize with lower water losses and higher water-use efficiencies. The magnitude of the effect varies greatly from crop to crop. However, for many crops in most U.S. regions, the benefits will likely be mostly or completely offset by increased stresses, such as higher temperatures, worsening air quality, and decreased ground moisture (Ch. 10: Ag & Rural). If crops and weeds are competing, then rising CO_2, in general, is more likely to stimulate the weed than the crop, with negative effects on production unless weeds are controlled.[54] Controlling weeds, however, is slightly more difficult, as rising CO_2 can reduce the efficacy of herbicides through enhanced gene transfer between crops and weedy relatives.[54]

Downstream impacts of rising CO_2 on plants can be significant. Increasing CO_2 concentrations provide an opportunity for cultivators to select plants that can exploit the higher CO_2 conditions and convert it to additional seed yield.[55] However, an area of emerging science suggests that rising CO_2 can reduce the nutritional quality (protein and micronutrients) of major crops.[56] In addition, rising CO_2 can reduce the protein concentration of pollen sources for bees.[57] Climate change also influences the amount and timing of pollen production. Increased CO_2 and temperature are correlated with earlier and greater pollen production and a longer allergy season (Ch. 13: Air Quality).

Please see Chapter 10: Ag & Rural, Chapter 6: Forests, and Ziska et al. (2016)[56] for more information on how climate change affects crops and plants.

Is climate change affecting U.S. wildfires?

It is difficult to determine how much of a role climate change has played in affecting recent wildfire activity in the United States. However, climate is generally considered to be a major driver of wildfire area burned. Over the last century, wildfire area burned in the mountainous areas of the western United States was greater during periods of low precipitation, drought, and high temperatures. Increased temperatures and drought severity with climate change will likely lead to increased fire area burned in fire-prone regions of the United States.

Climate is a major determinant of vegetation composition and productivity, which directly affect the type, amount, and structure of fuel available for fires. Climate also affects fuel moisture and the length of the season when fires are likely. Higher temperatures and lower precipitation result in lower fuel moisture, making fire spread more likely when an ignition occurs (if fuel is available). In mountainous areas, higher temperatures, lower snowpack, and earlier snowmelt lead to a longer fire season, lower fuel moisture, and higher likelihood of large fires.[58,59] Forest management practices are also a factor in determining the likelihood of ignition, as well as fire duration, extent, and intensity (Ch. 6: Forests).[23]

Long records of fire provided by tree-ring and charcoal evidence show that climate is the primary driver of fire on timescales ranging from years to millennia.[60] During the 20th century in the western United States, warm and dry conditions in spring and summer generally led to greater area burned in most places, particularly more mountainous and northerly locations (Figure A5.31).[60] The frequency of large forest fires (greater than 990 acres) has increased since the 1970s in the Northwest (1,000%) and Northern Rocky Mountains (889%), followed by forests in the Southwest (462%), Southern Rocky Mountains (274%), and Sierra Nevada (256%).[59] Dry forests in these regions account for about half of the total forest area burned since 1984. Globally, the length of the fire season (the time of year when climate and weather conditions are conducive to fire) has increased by 19% between 1979 and 2013, and it has become significantly longer over this period in most of the United States.[61]

With climate change, higher temperatures and more severe drought will likely lead to increased area burned in many ecosystems of the western and southeastern United States. By the mid-21st century, annual area burned is expected to increase 200%–300% in the contiguous western United States and 30% in the southeastern United States.[62] Over time, warmer temperatures and increased area burned can alter vegetation composition and productivity, which in turn affect fire occurrence. In arid regions, vegetation productivity may decrease sufficiently that fire will become less frequent. In other regions, climate may become less of a limiting factor for fire, and fuels may become more important in determining fire severity and extent.[63] In a warmer climate, wildfire is expected to be a catalyst for ecosystem change in all fire-prone ecosystems.

Area Burned by Large Wildfires Has Increased

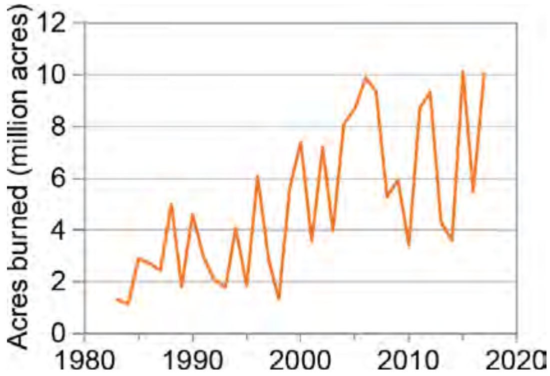


Figure A5.31: The figure shows the annual area burned by wildfires in the United States from 1983 to 2017. Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and interior Alaska over the past several decades, and the ten years with the largest area burned have all occurred since 2000. Source: adapted from EPA 2016.[64]

Does climate change increase the spread of mosquitoes or ticks?

Yes. Climate change can contribute to the spread of mosquitoes and ticks. A warmer climate enhances the suitability of habitats that were formerly too cold to support mosquito and tick populations, thus allowing these vectors, and the diseases they transmit, to invade new areas.

Mosquitoes and ticks are dependent on external sources for body heat, thus they develop from egg to adult more quickly under warmer conditions, producing more generations in a shorter time. Warming also speeds up population growth of the parasites and pathogens that mosquitoes transmit (including the agents of Zika virus, dengue fever, West Nile virus, and malaria), as well as the rate at which mosquitoes bite people and other hosts. Additionally, warmer conditions facilitate the spread of mosquitoes by increasing the length of the growing season and by decreasing the likelihood of winter die-offs due to extreme cold (Ch. 14: Human Health).[65]

Blacklegged (deer) ticks are the main vector (or transmitter) of Lyme disease in the United States. These ticks require a minimum number of days above freezing to persist. As a result, some northern and high-elevation areas cannot be invaded because the warm season is too short to allow each life stage to find an animal host before it needs to retreat underground. But as higher-latitude and higher-altitude areas continue to warm, blacklegged ticks may expand their range northward and higher in elevation (Figure A5.32) (see also Ch. 14: Human Health).[66,67] Studies show that ticks emerge earlier in the spring under warmer conditions, suggesting that the main Lyme disease season will move earlier in the spring.[65] Thus, earlier onset of warm spring conditions and warm summers and falls increase the establishment and resilience of tick populations.

Lyme Disease Cases Increase Under Warmer Conditions

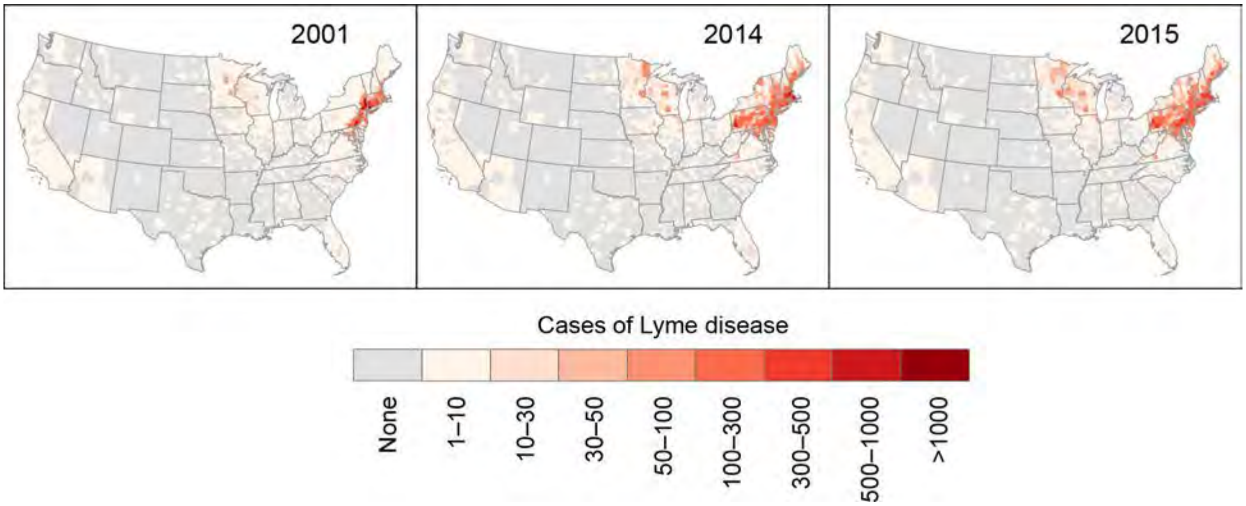


Figure A5.32: Reported cases of Lyme disease in 2001, 2014, and 2015 are shown by county for the contiguous United States. Both the distribution and total number of cases have increased from 2001 to 2014 and 2015, particularly in the Midwest and Northeast. Sources: CDC and ERT, Inc.

Acknowledgments

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