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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

During March-June 2012, the author team engaged in multiple technical discussions via teleconference (6 telecons) and email and in a day-long in-person meeting (April 27, 2012, in Washington, D.C.). Authors reviewed over 50 technical inputs provided by the public and a wide variety of technical and scholarly literature related to decision support, including reports from the National Research Council that provided recent syntheses of the field (America's Climate Choices series, especially the reports *Informing an Effective Response to Climate Change*[8] and *Informing Decisions in a Changing Climate*[3]). During the in-person meeting, authors reflected on the body of work informing the chapter and drafted a number of candidate critical messages that could be derived from the literature. Following the meeting, authors ranked these messages and engaged in expert deliberation via teleconference and email discussions in order to agree on a small number of key messages for the chapter.

Key message #1 Traceable Account

Decisions about how to address climate change can be complex, and responses will require a combination of adaptation and mitigation actions. Decision-makers – whether individuals, public officials, or others – may need help integrating scientific information into adaptation and mitigation decisions.

Description of evidence base

The sensitivity of the climate system to human activities, the extent to which mitigation policies are implemented, and the effects of other demographic, social, ecological, and economic changes on vulnerability also contribute to uncertainty in decision-making.

Uncertainties can make decision-making in the context of climate change especially challenging for several reasons, including the rapid pace of changes in physical and human systems, the lags between climate change and observed effects, the high economic and political stakes, the number and diversity of potentially affected stakeholders, the need to incorporate scientific information of varying confidence levels, and the values of stakeholders and decision-makers.[2,3]

An iterative decision process that incorporates constantly improving scientific information and learning through periodic reviews of decisions over time is helpful in the context of rapid changes in environmental conditions.[3,4] The National Research Council has concluded that an "iterative adaptive risk management" framework, in which decisions are adjusted over time to reflect new scientific information and decision-makers learn from experience, is appropriate for decisions about adaptation and ways to reduce future climate change, especially given uncertainties and advances in scientific understanding.[8,26]

Well-designed decision support processes, especially those in which there is a good match between the availability of scientific information and the capacity to use it, can result in more effective outcomes based on relevant information that is perceived as useful and applicable.[6]

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

N/A

Key message #2 Traceable Account

To be effective, decision support processes need to take account of the values and goals of the key stakeholders, evolving scientific information, and the perceptions of risk.

Description of evidence base

This message emphasizes that making a decision is more than picking the right tool and adopting its outcome. It is a process that should involve stakeholders, managers, and decision-makers to articulate and frame the decision, develop options, consider consequences (positive and negative), evaluate tradeoffs, make a decision, implement, evaluate, learn, and reassess.[1,8] Oftentimes having an inclusive, transparent decision process increases buy-in, regardless of whether a particular stakeholder's preferred option is chosen.[3] Decisions about investment in adaptation and mitigation measures occur in the context of uncertainty and high political and economic stakes, complicating the evaluation of information and its application in decision-making.[3,8] Decisions involve both scientific information and values – for example, how much risk is acceptable and what priorities and preferences are addressed.[2]

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

Key message #3 Traceable Account

Many decision support processes and tools are available. They can enable decision-makers to identify and assess response options, apply complex and uncertain information, clarify tradeoffs, strengthen transparency, and generate information on the costs and benefits of different choices.

Description of evidence base

Many decision support tools have been developed to support adaptive management in specific sectors or for specific issues. These tools include: risk assessments; geographic information system (GIS)-based analysis products; targeted projections for high-consequence events such as fires, floods, or droughts; vulnerability assessments; integrated assessment models; decision calendars; scenarios and scenario planning; and others.[3,8,84] Many of these tools have been validated scientifically and evaluated from the perspective of users. They are described in the sector and regional chapters of this assessment. In addition, a variety of clearing houses and data management systems provide access to decision support information and tools (for example, CAKE 2012; NatureServe 2012[39,85]).

There are many tools, some of which we discuss in the chapter, that are currently being used to make decisions that include a consideration of climate change and variability, or the impacts or vulnerabilities that would result from such changes.

Also important is the creation of a well-structured and transparent decision process that involves affected parties in problem framing, establishing decision criteria, fact finding, deliberation, and reaching conclusions.[1,8,26] These aspects of decision-making are often overlooked by those who focus more on scientific inputs and tools, but given the high stakes and remaining uncertainties, they are crucial for effective decision-making on adaptation and mitigation.

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

Key message #4 Traceable Account

Ongoing assessment processes should incorporate evaluation of decision support tools, their accessibility to decision-makers, and their application in decision processes in different sectors and regions.

Description of evidence base

As part of a sustained assessment, it is critical to understand the state of decision support, including what is done well and where we need to improve. At this point in time, there is a lack of literature that provides a robust evidence base to allow us to conduct this type of national, sector-scale assessment. Developing an evidence base would allow for a movement from case studies to larger-scale assessment across decision support and would allow us to better understand how to better utilize what decision support is available and understand what needs to be improved to support adaptation and mitigation decisions in different sectors and regions.

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

Key message #5 Traceable Account

Steps to improve collaborative decision processes include developing new decision support tools and building human capacity to bridge science and decision-making.

Description of evidence base

There are many challenges in communicating complex scientific information to decision makers and the public,[11] and while "translation" of complex information is one issue, there are many others. Defining the scope and scale of the relevant climate change problem can raise both scientific and social questions. These questions require both scientific insights and consideration of values and social constructs, and require that participants engage in mutual learning and the co-production of relevant knowledge.[10] Boundary processes that are collaborative and iterative[18] among scientists, stakeholders, and decision-makers, such as joint fact finding and collaborative adaptive management, foster ongoing dialogue and increasing participants' understanding of policy problems and information and analysis necessary to evaluate decision options.[12,13] Analysis of the conditions that contribute to their effectiveness of boundary processes is an emerging area of study.[13]

A large body of literature notes that the ability of decision-makers to use data and tools has not kept pace with the rate at which new tools are developed, pointing to a need for "science translators" who can help decision-makers efficiently access and properly use data and tools that would be helpful in making more informed decisions in the context of climate change.[3,4,8,83,133] The U.S. climate research effort has been strongly encouraged to improve integration of social and ecological sciences and to develop the capacity for decision support to help address the need to effectively incorporate advances in climate science into decision-making.[135]

New information and remaining uncertainties

N/A

Assessment of confidence based on evidence

N/A

CHAPTER 27
MITIGATION

Convening Lead Authors

Henry D. Jacoby, Massachusetts Institute of Technology

Anthony C. Janetos, Boston University

Lead Authors

Richard Birdsey, U.S. Forest Service

James Buizer, University of Arizona

Katherine Calvin, Pacific Northwest National Laboratory, University of Maryland

Francisco de la Chesnaye, Electric Power Research Institute

David Schimel, NASA Jet Propulsion Laboratory

Ian Sue Wing, Boston University

Contributing Authors

Reid Detchon, United Nations Foundation

Jae Edmonds, Pacific Northwest National Laboratory, University of Maryland

Lynn Russell, Scripps Institution of Oceanography, University of California, San Diego

Jason West, University of North Carolina

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27 MITIGATION

Key Messages

1. **Carbon dioxide is removed from the atmosphere by natural processes at a rate that is roughly half of the current rate of emissions from human activities. Therefore, mitigation efforts that only stabilize global emissions will not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase. The same is true for other long-lived greenhouse gases.**
2. **To meet the lower emissions scenario (B1) used in this assessment, global mitigation actions would need to limit global carbon dioxide emissions to a peak of around 44 billion tons per year within the next 25 years and decline thereafter. In 2011, global emissions were around 34 billion tons, and have been rising by about 0.9 billion tons per year for the past decade. Therefore, the world is on a path to exceed 44 billion tons per year within a decade.**
3. **Over recent decades, the U.S. economy has emitted a decreasing amount of carbon dioxide per dollar of gross domestic product. Between 2008 and 2012, there was also a decline in the total amount of carbon dioxide emitted annually from energy use in the United States as a result of a variety of factors, including changes in the economy, the development of new energy production technologies, and various government policies.**
4. **Carbon storage in land ecosystems, especially forests, has offset around 17% of annual U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" may not be sustainable.**
5. **Both voluntary activities and a variety of policies and measures that lower emissions are currently in place at federal, state, and local levels in the United States, even though there is no comprehensive national climate legislation. Over the remainder of this century, aggressive and sustained greenhouse gas emission reductions by the United States and by other nations would be needed to reduce global emissions to a level consistent with the lower scenario (B1) analyzed in this assessment.**

Mitigation refers to actions that reduce the human contribution to the planetary greenhouse effect. Mitigation actions include lowering emissions of greenhouse gases like carbon dioxide and methane, and particles like black carbon (soot) that have a warming effect. Increasing the net uptake of carbon dioxide through land-use change and forestry can make a contribution as well. As a whole, human activities result in higher global concentrations of greenhouse gases and to a warming of the planet – and the effect is increased by various self-reinforcing cycles in the Earth system (such as the way melting sea ice results in more dark ocean water, which absorbs more heat, and leads to more sea ice loss). Also, the absorption of increased carbon dioxide by the oceans is leading to increased ocean acidity with adverse effects on marine ecosystems.

Four mitigation-related topics are assessed in this chapter. First, it presents an overview of greenhouse gas emissions and their climate influence to provide a context for discussion of mitigation efforts. Second, the chapter provides a survey of activities contributing to U.S. emissions of carbon dioxide and other greenhouse gases. Third, it provides a summary of current government and voluntary efforts to manage these emissions. Finally, there is an assessment of the adequacy of these efforts relative to the magnitude of the climate change threat and a discussion of preparation for potential future action.

While the chapter presents a brief overview of mitigation issues, it does not provide a comprehensive discussion of policy options, nor does it attempt to review or analyze the range of technologies available to reduce emissions.

These topics have also been the subject of other assessments, including those by the National Academy of Sciences[1] and the U.S. Department of Energy.[2] Mitigation topics are addressed throughout this report (see Ch. 4: Energy, Key Message 5; Ch. 5: Transportation, Key Message 4; Ch. 7: Forests, Key Message 4; Ch. 9: Human Health, Key Message 4; Ch. 10: Energy, Water, and Land, Key Messages 1, 2, 3; Ch. 13: Land Use & Land Cover Change, Key Messages 2, 4; Ch. 15: Biogeochemical Cycles, Key Message 3; Ch. 26: Decision Support, Key Messages 1, 2, 3; Appendix 3: Climate Science Supplemental Message 5; Appendix 4: FAQs N, S, X, Y, Z).

Emissions, Concentrations, and Climate Forcing

Setting mitigation objectives requires knowledge of the Earth system processes that determine the relationship among emissions, atmospheric concentrations and, ultimately, climate. Human-caused climate change results mainly from the increasing atmospheric concentrations of greenhouse gases.[3] These gases cause radiative "forcing" – an imbalance of heat trapped by the atmosphere compared to an equilibrium state. Atmospheric concentrations of greenhouse gases are the result of the history of emissions and of processes that remove them from the atmosphere; for example, by "sinks" like growing forests.[4] The fraction of emissions that remains in the atmosphere, which is different for each greenhouse gas, also varies over time as a result of Earth system processes.

The impact of greenhouse gases depends partly on how long each one persists in the atmosphere.[5] Reactive gases like methane and nitrous oxide are destroyed chemically in the atmosphere, so the relationships between emissions and atmospheric concentrations are determined by the rate of those reactions. The term "lifetime" is often used to describe the speed with which a given gas is removed from the atmosphere. Methane has a relatively short lifetime (largely removed within a decade or so, depending on conditions), so reductions in emissions can lead to a fairly rapid decrease in concentrations as the gas is oxidized in the atmosphere.[6] Nitrous oxide has a much longer lifetime, taking more than 100 years to be substantially removed.[7] Other gases in this category include industrial gases, like those used as solvents and in air conditioning, some of which persist in the atmosphere for hundreds or thousands of years.

Carbon dioxide (CO_2) does not react chemically with other gases in the atmosphere, so it does not, strictly speaking, have a "lifetime."[8] Instead, the relationship between emissions and concentrations from year to year is determined by patterns of release (for example, through burning of fossil fuels) and uptake (for example, by vegetation and by the ocean).[9] Once CO_2 is emitted from any source, a portion of it is removed from the atmosphere over time by plant growth and absorption by the oceans, after which it continues to circulate in the land-atmosphere-ocean system until it is finally converted into stable forms in soils, deep ocean sediments, or other geological repositories (Figure 27.1).

Of the carbon dioxide emitted from human activities in a year, about half is removed from the atmosphere by natural processes within a century, but around 20% continues to circu-

Human Activities and the Global Carbon Dioxide Budget

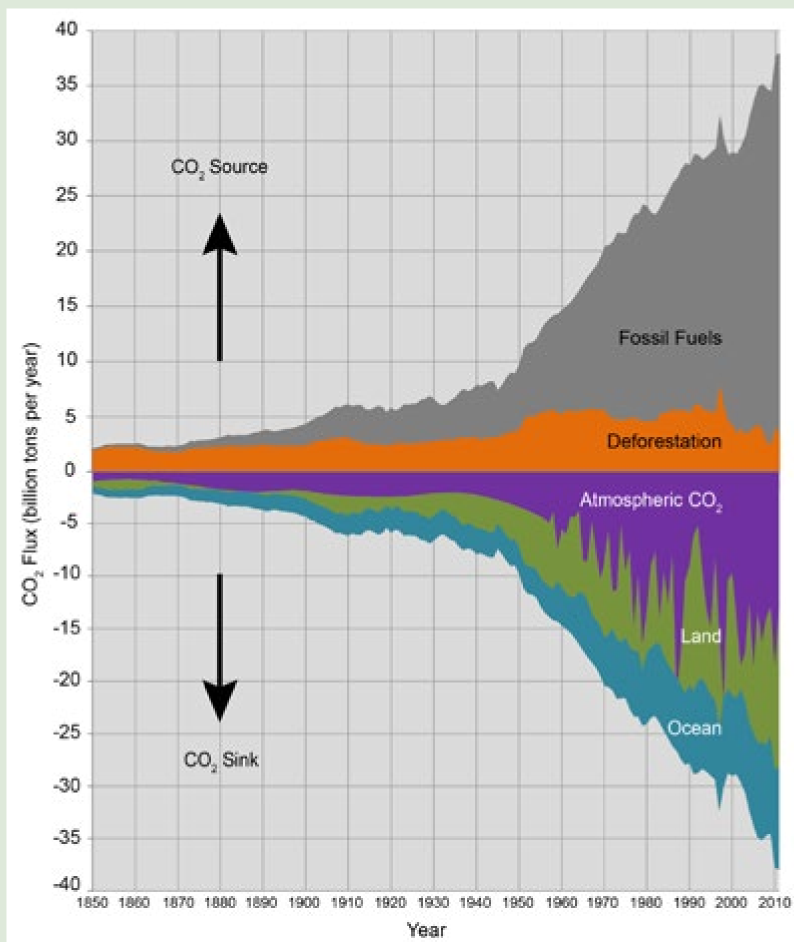

Figure 27.1. Figure shows human-induced changes in the global carbon dioxide budget roughly since the beginning of the Industrial Revolution. Emissions from fossil fuel burning are the dominant cause of the steep rise shown here from 1850 to 2012. (Global Carbon Project 2010, 2012[10]).

late and to affect atmospheric concentrations for thousands of years.[11] Stabilizing or reducing atmospheric carbon dioxide concentrations, therefore, requires very deep reductions in future emissions – ultimately approaching zero – to compensate for past emissions that are still circulating in the Earth system. Avoiding future emissions, or capturing and storing them in stable geological storage, would prevent carbon dioxide from entering the atmosphere, and would have very long-lasting effects on atmospheric concentrations.

In addition to greenhouse gases, there can be climate effects from fine particles in the atmosphere. An example is black carbon (soot), which is released from coal burning, diesel engines, cooking fires, wood stoves, wildfires, and other combustion sources. These particles have a warming influence, especially when they absorb solar energy low in the atmosphere.[12] Other particles, such as those formed from sulfur dioxide released during coal burning, have a cooling effect by reflecting some of the sun's energy back to space or by increasing the brightness of clouds (see: Ch. 2: Our Changing Climate; Appendix 3: Climate Science Supplement; and Appendix 4: FAQs).

The effect of each gas is related to both how long it lasts in the atmosphere (the longer it lasts, the greater its influence) and its potency in trapping heat. The warming influence of different gases can be compared using "global warming potentials" (GWP), which combine these two effects, usually added up over a 100-year time period. Global warming potentials are referenced to carbon dioxide – which is defined as having a GWP of 1.0 – and the combined effect of multiple gases is denoted in carbon dioxide equivalents, or CO_2-e.

The relationship between emissions and concentrations of gases can be modeled using Earth System Models.[4] Such models apply our understanding of biogeochemical processes that remove greenhouse gas from the atmosphere to predict their future concentrations. These models show that stabilizing CO_2 *emissions* would not stabilize its atmospheric concentrations but instead result in a concentration that would increase at a relatively steady rate. Stabilizing atmospheric *concentrations* of CO_2 would require reducing emissions far below present-day levels. Concentration and emissions scenarios, such as the recently developed Representative Concentration Pathways (RCPs) and scenarios developed earlier by the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES), are used in Earth System Models to study potential future climates. The RCPs span a range of atmospheric targets for use by climate modelers,[13,14] as do the SRES cases. These global analyses form a framework within which the climate contribution of U.S. mitigation efforts can be assessed. In this report, special attention is given to the SRES A2 scenario (similar to RCP 8.5), which assumes continued increases in emissions, and the SRES B1 scenario (close to RCP 4.5), which assumes a substantial reduction of emissions (Ch. 2: Our Changing Climate; Appendix 5: Scenarios and Models).

Geoengineering

Geoengineering has been proposed as a third option for addressing climate change in addition to, or alongside, mitigation and adaptation. Geoengineering refers to intentional modifications of the Earth system as a means to address climate change. Three types of activities have been proposed: 1) carbon dioxide removal (CDR), which boosts CO_2 removal from the atmosphere by various means, such as fertilizing ocean processes and promoting land-use practices that help take up carbon, 2) solar radiation management (SRM), which reflects a small percentage of sunlight back into space to offset warming from greenhouse gases,[15] and 3) direct capture and storage of CO_2 from the atmosphere.[16]

Current research suggests that SRM or CDR could diminish the impacts of climate change. However, once undertaken, sudden cessation of SRM would exacerbate the climate effects on human populations and ecosystems, and some CDR might interfere with oceanic and terrestrial ecosystem processes.[17] SRM undertaken by itself would not slow increases in atmospheric CO_2 concentrations, and would therefore also fail to address ocean acidification. Furthermore, existing international institutions are not adequate to manage such global interventions. The risks associated with such purposeful perturbations to the Earth system are thus poorly understood, suggesting the need for caution and comprehensive research, including consideration of the implicit moral hazards.[18]

Section 1: U.S. Emissions and Land-Use Change

Industrial, Commercial, and Household Emissions

U.S. greenhouse gas emissions, not accounting for uptake by land use and agriculture (see Figure 27.3), rose to as high as 7,260 million tons CO_2-e in 2007, and then fell by about 9% between 2008 and 2012.[19] Several factors contributed to the decline, including the reduction in energy use in response to the 2008-2010 recession, the displacement of coal in electric generation by lower-priced natural gas, and the effect of federal and state energy and environmental policies.[20]

Carbon dioxide made up 84% of U.S. greenhouse gas emissions in 2011. Forty-one percent of these emissions were attributable to liquid fuels (petroleum), followed closely by solid fuels (principally coal in electric generation), and to a lesser extent by natural gas.[20] The two dominant production sectors responsible for these emissions are electric power generation (coal and gas) and transportation (petroleum). Flaring and cement manufacture together account for less than 1% of the total. If emissions from electric generation are allocated to their various end-uses, transportation is the largest CO_2 source, contributing a bit over one-third of the total, followed by industry at slightly over a quarter, and residential use and the commercial sector at around one-fifth each.

A useful picture of historical patterns of carbon dioxide emissions can be constructed by decomposing the cumulative change in emissions from a base year into the contributions of five driving forces: 1) decline in the CO_2 content of energy use, as with a shift from coal to natural gas in electric generation, 2) reduction in energy intensity – the energy needed to produce each unit of gross domestic product (GDP) – which results from substitution responses to energy prices, changes in the composition of the capital stock, and both autonomous and price-induced technological change, 3) changes in the structure of the economy, such as a decline in energy-intensive industries and an increase in services that use less energy, 4) growth in per capita GDP, and 5) rising population.

Over the period 1963-2008, annual U.S. carbon dioxide emissions slightly more than doubled, because growth in emissions potential attributable to increases in population and GDP per person outweighed reductions contributed by lowered energy and carbon intensity and changes in economic structure (Figure 27.2). Each series in the figure illustrates the quantity of cumulative emissions since 1963 that would have been generated by the effect of the associated driver. By 2008, fossil fuel burning had increased CO_2 emissions by 2.7 billion tons over 1963 levels. However, by itself the observed decline in energy would have reduced emissions by 1.8 billion tons, while the observed increase in per capita GDP would have increased emissions by more than 5 billion tons.

After decades of increases, CO_2 emissions from energy use (which account for 97% of total U.S. emissions) declined by around 9% between 2008 and 2012, largely due to a shift from coal to less CO_2-intensive natural gas for electricity production.[19] Trends in driving forces shown in Figure 27.2 are expected to continue in the future, though their relative contributions are subject to significant uncertainty. The reference case projection by the U.S. Energy Information Administration (EIA) shows their net effect being a slower rate of CO_2 emissions growth than in the past, with roughly constant energy sector emissions to 2040.[22] It must be recognized, however, that emissions from energy use rise and fall from year to year, as the aforementioned driving forces vary.

Drivers of U.S. Fossil Emissions

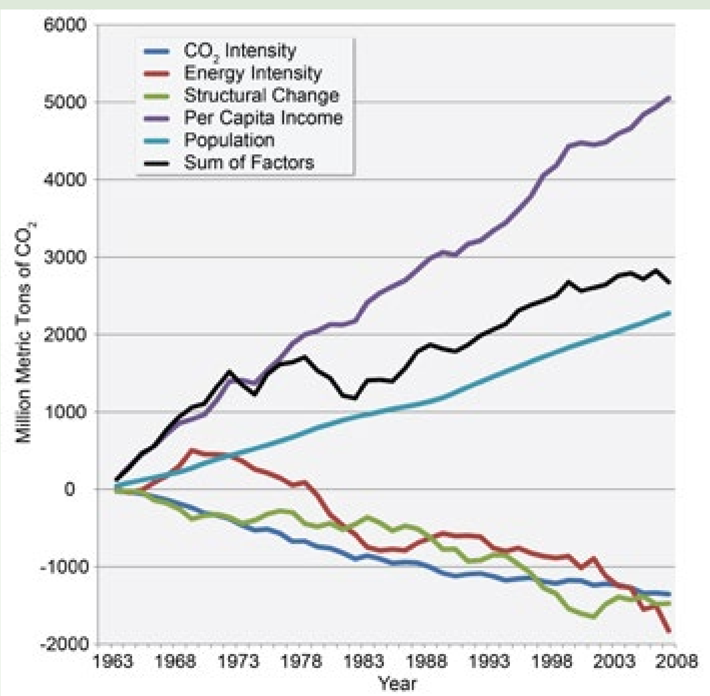

Figure 27.2. This graph depicts the changes in carbon dioxide (CO_2) emissions over time as a function of five driving forces: 1) the amount of CO_2 produced per unit of energy (CO_2 intensity); 2) the amount of energy used per unit of gross domestic product (energy intensity); 3) structural changes in the economy; 4) per capita income; and 5) population. Although CO_2 intensity and especially energy intensity have decreased significantly and the structure of the U.S. economy has changed, total CO_2 emissions have continued to rise as a result of the growth in both population and per capita income. (Baldwin and Sue Wing, 2013[21]).

The primary non-CO_2 gas emissions in 2011 were methane (9% of total CO_2-e emissions), nitrous oxide (5%), and a set of industrial gases (2%). U.S. emissions of each of these gases have been roughly constant over the past half-dozen years.[22] Emissions of methane and nitrous oxide have been roughly constant over the past couple of decades, but there has been an increase in the industrial gases as some are substituted for ozone-destroying substances controlled by the Montreal Protocol.[23]

Yet another warming influence on the climate system is black carbon (soot), which consists of fine particles that result mainly from incomplete combustion of fossil fuels and biomass. Long a public health concern, black carbon particles absorb solar radiation during their short life in the atmosphere (days to weeks). When deposited on snow and ice, these particles darken the surface and reduce the reflection of incoming solar radiation back to space. These particles also influence cloud formation in ways yet poorly quantified.[24]

Land Use, Forestry, and Agriculture

The main stocks of carbon in its various biological forms (plants and trees, dead wood, litter, soil, and harvested products) are estimated periodically and their rate of change, or flux, is calculated as the average annual difference between two time periods. Estimates of carbon stocks and fluxes for U.S. lands are based on land inventories augmented with data from ecosystem studies and production reports.[25,26]

U.S. lands were estimated to be a net sink of between approximately 640 and 1,074 million tons CO_2-e in the late 2000s.[26,27] Estimates vary depending on choice of datasets, models, and methodologies (see Ch. 15: Biogeochemical Cycles, "Estimating the U.S. Carbon Sink," for more discussion). This net land sink effect is the result of sources (from crop production, livestock production, and grasslands) and sinks (in forests, urban trees, and wetlands). Sources of carbon have been relatively stable over the last two decades, but sinks have been more variable. Long-term trends suggest significant emissions from forest clearing in the early 1900s followed by a sustained period of net uptake from forest regrowth over the last 70 years.[28] The amount of carbon taken up by U.S. land sinks is dominated by forests, which have annually absorbed 7% to 24% (with a best estimate of about 16%) of fossil fuel CO_2 emissions in the U.S. over the past two decades.[20]

Sources and Sinks in U.S. Agriculture and Forests

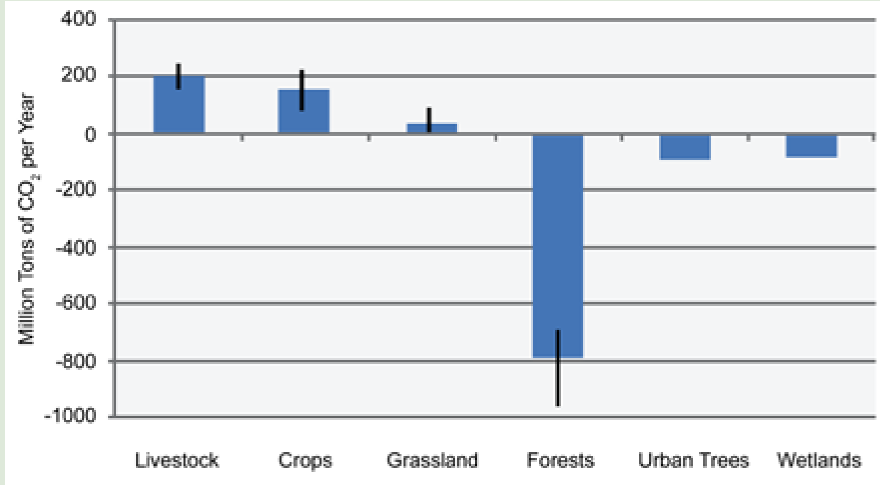

Figure 27.3 Graph shows annual average greenhouse gas emissions from land use including livestock and crop production, but does not include fossil fuels used in agricultural production. Forests are a significant "sink" that absorbs carbon dioxide from the atmosphere. All values shown are for 2008, except wetlands, which are shown for 2003. (Pacala et al. 2007;[27] USDA 2011[26]).

The persistence of the land sink depends on the relative effects of several interacting factors: recovery from historical land-use change, atmospheric CO_2 and nitrogen deposition, natural disturbances, and the effects of climate variability and change – particularly drought, wildfires, and changes in the length of the growing season. Deforestation continues to cause an annual loss of 877,000 acres (137,000 square miles) of forested land, offset by a larger area gain of new forest of about 1.71 million acres (268,000 square miles) annually.[29] Since most of the new forest is on relatively low-productivity lands of the Intermountain West, and much of the deforestation occurs on high-productivity lands in the East, recent land-use changes have decreased the potential for future carbon storage.[30] The positive effects of increasing carbon dioxide concentration and nitrogen deposition on carbon storage are not likely to be as large as the negative effects of land-use change and disturbances.[31] In some regions, longer growing seasons associated with climate change may increase annual productivity.[32] Droughts and other disturbances, such as fire and insect infestations, have already turned some U.S. land regions from carbon sinks into carbon sources (see Ch. 13: Land Use & Land Cover Change and Ch. 15: Biogeochemical Cycles).[31] The current land sink may not be sustainable for more than a few more decades,[33] though there is a lack of consistency in published results about the relative effects of disturbance and other factors on net land-use emissions.[31,34]

Section 2: Activities Affecting Emissions

Early and large reductions in global emissions would be necessary to achieve the lower emissions scenarios (such as the lower B1 scenario; see Ch. 2: Our Changing Climate) analyzed in this assessment. The principal types of national actions that could effect such changes include putting a price on emissions, setting regulations and standards for activities that cause emissions, changing subsidy programs, and direct federal expenditures. Market-based approaches include cap and trade programs that establish markets for trading emissions permits, analogous to the Clean Air Act provisions for sulfur dioxide reductions. None of these price-based measures has been implemented at the national level in the United States, though cap and trade systems are in place in California and in the Northeast's Regional Greenhouse Gas Initiative. Moreover, a wide range of governmental actions are underway at federal, state, regional, and city levels using other measures, and voluntary efforts, that can reduce the U.S. contribution to total global emissions. Many, if not most of these programs are motivated by other policy objectives – energy, transportation, and air pollution – but some are directed specifically at greenhouse gas emissions, including:

- reduction in CO_2 emissions from energy end-use and infrastructure through the adoption of energy-efficient components and systems – including buildings, vehicles, manufacturing processes, appliances, and electric grid systems;

- reduction of CO_2 emissions from energy supply through the promotion of renewables (such as wind, solar, and bio-energy), nuclear energy, and coal and natural gas electric generation with carbon capture and storage; and

- reduction of emissions of non-CO_2 greenhouse gases and black carbon; for example, by lowering methane emissions from energy and waste, transitioning to climate-friendly alternatives to hydrofluorocarbons (HFCs), cutting methane and nitrous oxide emissions from agriculture, and improving combustion efficiency and means of particulate capture.

Programs underway that reduce carbon dioxide emissions include the promotion of solar, nuclear, and wind power and efficient vehicles

Federal Actions

The Federal Government has implemented a number of measures that promote energy efficiency, clean technologies, and alternative fuels.[35] A sample of these actions is provided in Table 27.1 and they include greenhouse gas regulations, other rules and regulations with climate co-benefits, various standards and subsidies, research and development, and federal procurement practices.

The U.S. Environmental Protection Agency (EPA) has a 40-year history of regulating the concentration and deposition of criteria pollutants (six common air pollutants that affect human health). A 2012 Supreme Court decision upheld the EPA's finding that greenhouse gases "endanger public health and welfare."[36] This ruling added the regulation of greenhouse gas emissions to the Agency's authority under the Clean Air Act. Actions taken and proposed under the new authority have focused on road transport and electric power generation.

The U.S. Department of Energy (DOE) provides most of the funding for a broad range of programs for energy research,

development, and demonstration. DOE also has the authority to regulate the efficiency of appliances and building codes for manufactured housing. In addition, most of the other federal agencies – including the Departments of Defense, Housing and Urban Development, Transportation, and Agriculture – have programs related to greenhouse gas mitigation.

The Administration's Climate Action Plan[37] builds on these activities with a broad range of mitigation, adaptation, and preparedness measures. The mitigation elements of the plan are in part a response to the commitment made during the 2010 Cancun Conference of the Parties of the United Nations Framework Convention on Climate Change to reduce U.S. emissions of greenhouse gases by 17% below 2005 levels by 2020. Actions proposed in the Plan include: 1) limiting carbon emissions from both new and existing power plants, 2) continuing to increase the stringency of fuel economy standards for automobiles and trucks, 3) continuing to improve energy efficiency in the buildings sector, 4) reducing the emissions of non-CO_2 greenhouse gases through a variety of measures, 5) increasing federal investments in cleaner, more efficient energy sources for both power and transportation, and 6) identifying new approaches to protect and restore our forests and other critical landscapes, in the presence of a changing climate.

City, State, and Regional Actions

Jurisdiction for greenhouse gases and energy policies is shared between the federal government and the states.[1] For example, states regulate the distribution of electricity and natural gas to consumers, while the Federal Energy Regulatory Commission regulates wholesale sales and transportation of natural gas and electricity. In addition, many states have adopted climate initiatives as well as energy policies that reduce greenhouse gas emissions. For a survey of many of these state activities, see Table 27.2. Many cities are taking similar actions.

The most ambitious state activity is California's Global Warming Solutions Act (AB 32), a law that sets a state goal to reduce greenhouse gas emissions to 1990 levels by 2020. The state program caps emissions and uses a market-based system of trading in emissions credits (cap and trade), as well as a number of regulatory actions. The most well-known, multi-state effort has been the Regional Greenhouse Gas Initiative (RGGI), formed by ten northeastern and Mid-Atlantic states (though New Jersey exited in 2011). RGGI is a cap and trade system applied to the power sector with revenue from allowance auctions directed to investments in efficiency and renewable energy.

Voluntary Actions

Corporations, individuals, and non-profit organizations have initiated a host of voluntary actions. The following examples give the flavor of the range of efforts:

- The Carbon Disclosure Project has the largest global collection of self-reported climate change and water-use information. The system enables companies to measure, disclose, manage, and share climate change and water-use information. Some 650 U.S. signatories include banks, pension funds, asset managers, insurance companies, and foundations.

- Many local governments are undertaking initiatives to reduce greenhouse gas emissions within and outside of their organizational boundaries.[38] For example, over 1,055 municipalities from all 50 states have signed the U.S. Mayors Climate Protection Agreement,[39] and many of these communities are actively implementing strategies to reduce their greenhouse gas footprint.

- Under the American College and University Presidents' Climate Commitment (ACUPCC), 679 institutions have pledged to develop plans to achieve net-neutral climate emissions through a combination of on-campus changes and purchases of emissions reductions elsewhere.

- Voluntary compliance with efficiency standards developed by industry and professional associations, such as the building codes of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is widespread.

- Federal voluntary programs include Energy STAR, a labeling program that identifies energy efficient products for use in residential homes and commercial buildings and plants, and programs and partnerships devoted to reducing methane emissions from fossil fuel production and landfill sources and high GWP emissions from industrial activities and agricultural conservation programs.

Costs of Emissions Reductions

The national cost of achieving U.S. emissions reductions over time depends on the level of reduction sought and the particular measures employed. Studies of price-based policies, such as a cap and trade system, indicate that a 50% reduction in emissions by 2050 could be achieved at a cost of a year or two of projected growth in gross domestic product over the period (for example, Paltsev et al. 2009; EIA 2009[40]). However, because of differences in analysis method, and in assumptions about economic growth and technology change, cost projections vary considerably even for a policy applying price penalties.[41] Comparisons of emissions reduction by prices versus regulations show that a regulatory approach can cost substantially more than a price-based policy.[42]

Co-benefits for air pollution and human health

Actions to reduce greenhouse gas emissions can yield co-benefits for objectives apart from climate change, such as energy security, health, ecosystem services, and biodiversity.[43,44] The co-benefits for reductions in air pollution have received particular attention. Because air pollutants and greenhouse gases share common sources, particularly from fossil fuel combustion, actions to reduce greenhouse gas emissions also reduce air pollutants. While some greenhouse gas reduction measures might increase other emissions, broad programs to reduce greenhouse gases across an economy or a sector can reduce air pollutants markedly.[14,45] (Unfortunately for climate mitigation, cutting sulfur dioxide pollution from coal burning also reduces the cooling influence of reflective particles formed from these emissions in the atmosphere.[46])

There is significant interest in quantifying the air pollution and human health co-benefits of greenhouse gas mitigation, particularly from the public health community,[44,47] as the human health benefits can be immediate and local, in contrast to the long-term and widespread effects of climate change.[48] Many studies have found that monetized health and pollution control benefits can be of similar magnitude to abatement costs (for example, Nemet et al. 2010; Burtraw et al. 2003[48,49]). Methane reductions have also been shown to generate health benefits from reduced ozone.[50] Similarly, in developing nations, reducing black carbon from household cook stoves substantially reduces air pollution-related illness and death.[51] Ancillary health benefits in developing countries typically exceed those in developed countries for a variety of reasons.[48] But only in very few cases are these ancillary benefits considered in analyses of climate mitigation policies.

Section 3: Preparation for Potential Future Mitigation Action

To meet the emissions reduction in the lower (B1) scenario used in this assessment (Ch. 2: Our Changing Climate) under reasonable assumptions about managing costs, annual global CO_2 emissions would need to peak at around 44 billion tons within the next 25 years or so and decline steadily for the rest of the century. At the current rate of emissions growth, the world is on a path to exceed the 44 billion ton level within a decade (see "Emissions Scenarios and RCPs"). Thus achievement of a global emissions path consistent with the B1 scenario will require strenuous action by all major emitters.

Policies already enacted and other factors lowered U.S. emissions in recent years. The Annual Energy Outlook prepared by the EIA, which previously forecasted sustained growth in emissions, projected in 2013 that energy-related U.S. CO_2 emissions would remain roughly constant for the next 25 years.[22]

Moreover, through the President's Climate Action Plan, the Administration has committed to additional measures not yet reflected in the EIA's projections, with the goal of reducing emissions about 17% below 2005 levels by 2020. Still, additional and stronger U.S. action, as well as strong action by other major emitters, will be needed to meet the long-term global emission reductions reflected in the B1 scenario.

Achieving the B1 emissions path would require substantial decarbonization of the global economy by the end of this century, implying a fundamental transformation of the global energy system. Details of the energy mix along the way differ among analyses, but the implied involvement by the U.S. can be seen in studies carried out under the U.S. Climate Change Science Program[54] and the Energy Modeling Forum.[55,56] In these studies, direct burning of coal without carbon capture is essentially excluded from the power system, and the same holds for natural gas toward the end of the century – to be replaced by some combination of coal or gas with carbon capture and storage, nuclear generation, and renewables. Biofuels and electricity are projected to substitute for oil in the transport sector. A substantial component of the task is accomplished with demand reduction, through efficiency improvement, conservation, and shifting to an economy less dependent on energy services.

The challenge is great enough even starting today, but delay by any of the major emitters makes meeting any such target even more difficult and may rule out some of the more ambitious goals.[54,55] A study of the climate change threat and potential responses by the U.S. National Academies therefore concludes that there is "an urgent need for U.S. action to reduce greenhouse emissions."[57] The National Research Council (NRC) goes on to suggest alternative national-level strategies that might be followed, including an economy-wide system of prices on greenhouse gas emissions and a portfolio of possible regulatory measures and subsidies. Deciding these matters will be a continuing task, and U.S. Administrations and Congress face a long series of choices about whether to take additional mitigation actions and how best to do it. Two supporting activities will help guide this process: opening future technological options and development of ever-more-useful assessments of the cost effectiveness and benefits of policy choices.

Emissions scenarios and RCPs

The Representative Concentration Pathways (RCPs) specify alternative limits to human influence on the Earth's energy balance, stated in watts per square meter (W/m^2) of the Earth's surface.[13,52] The A2 emissions scenario implies atmospheric concentrations with radiative forcing slightly lower than the highest RCP, which is 8.5 W/m^2. The lower limits, at 6.0, 4.5 and 2.6 W/m^2, imply ever-greater mitigation efforts. The B1 scenario (rapid emissions reduction) is close to the 4.5 W/m^2 RCP[53] and to a similar case (Level 2) analyzed in a previous federal study.[54] Those assessments find that, to limit the economic costs, annual global CO_2 emissions from fossil fuels and industrial sources like cement manufacture, need to peak by 2035 to 2040 at around 44 billion tons of CO_2, and decline thereafter. The scale of the task can be seen in the fact that these global emissions were already at 34 billion tons CO_2 in 2011, and over the previous decade they rose at around 0.92 billion tons of CO_2 per year.[10] The lowest RCP would require an even more rapid turnaround and negative net emissions – that is, removing more CO_2 from the air than is emitted globally – in this century.[52]

Many technologies are potentially available to accomplish emissions reduction. They include ways to increase the efficiency of fossil energy use and facilitate a shift to low-carbon energy sources, sources of improvement in the cost and performance of renewables (for example, wind, solar, and bioenergy) and nuclear energy, ways to reduce the cost of carbon capture and storage, means to expand terrestrial sinks through management of forests and soils and increased agricultural productivity,[2] and phasing down HFCs. In addition to the research and development carried out by private sector firms with their own funds, the Federal Government traditionally supports major programs to advance these technologies. This support is accomplished in part by credits and deductions in the tax code, and in part by federal expenditure. For example, the 2012 federal budget devoted approximately $6 billion to clean energy technologies.[58] Success in these ventures, lowering the cost of greenhouse gas reduction, can make a crucial contribution to future policy choices.[1]

Because they are in various stages of market maturity, the costs and effectiveness of many of these technologies remain uncertain: continuing study of their performance is important to understanding their role in future mitigation decisions.[59] In addition, evaluation of broad policies and particular mitigation measures requires frameworks that combine information from a range of disciplines. Study of mitigation in the near future can be done with energy-economic models that do not assume large changes in the mix of technologies or changes in the structure of the economy. Analysis over the time spans relevant to stabilization of greenhouse gas concentrations, however, requires Integrated Assessment Models, which consider all emissions drivers and policy measures that affect them, and that take account of how they are related to the larger economy and features of the climate system.[54,55,60] This type of analysis is also useful for exploring the relations between mitigation and measures to adapt to a changing climate.

Continued development of these analytical capabilities can help support decisions about national mitigation and the U.S. position in international negotiations. In addition, as shown above, mitigation is being undertaken by individuals and firms as well as by city, state, and regional governments. The capacity for mitigation from individual and household behavioral changes, such as increasing energy end-use efficiency with available technology, is known to be large.[63] Although there is capacity, there is not always broad acceptance of those behavioral changes, nor is there sufficient understanding of how to design programs to encourage such changes.[64] Behavioral and institutional research on how such choices are made and the results evaluated would be extremely beneficial. For many of these efforts, understanding of cost and effectiveness is limited, as is understanding of aspects of public support and institutional performance; so additional support for studies of these activities is needed to ensure that resources are efficiently employed.

Interactions between adaptation and mitigation

There are various ways in which mitigation efforts and adaptation measures are interdependent (see Ch. 28: Adaptation). For example, the use of plant material as a substitute for petroleum-based transportation fuels or directly as a substitute for burning coal or gas for electricity generation has received substantial attention.[61] But land used for mitigation purposes is potentially not available for food production, even as the global demand for agricultural products continues to rise.[62] Conversely, land required for adaptation strategies, like setting aside wildlife corridors or expanding the extent of conservation areas, is potentially not available for mitigation involving the use of plant material, or active management practices to enhance carbon storage in vegetation or soils. These possible interactions are poorly understood but potentially important, especially as climate change itself affects vegetation and ecosystem productivity and carbon storage. Increasing agricultural productivity to adapt to climate change can also serve to mitigate climate change.

Section 4: Research Needs

- Engineering and scientific research is needed on the development of cost-effective energy use technologies (devices, systems, and control strategies) and energy supply technologies that produce little or no CO_2 or other greenhouse gases.

- Better understanding of the relationship between emissions and atmospheric greenhouse gas concentrations is needed to more accurately predict how the atmosphere and climate system will respond to mitigation measures.

- The processes controlling the land sink of carbon in the U.S. require additional research, including better monitoring and analysis of economic decision-making about the fate of land and how it is managed, as well as the inherent ecological processes and how they respond to the climate system.

- Uncertainties in model-based projections of greenhouse gas emissions and of the effectiveness and costs of policy measures need to be better quantified. Exploration is needed of the effects of different model structures, assumptions about model parameter values, and uncertainties in input data.

- Social and behavioral science research is needed to inform the design of mitigation measures for maximum participation and to prepare a consistent framework for assessing cost effectiveness and benefits of both voluntary mitigation efforts and regulatory and subsidy programs.

Table 27.1. A number of existing federal laws and regulations target ways to reduce future climate change by decreasing greenhouse gas emissions emitted by human activities.

Sample Federal Mitigation Measures
Greenhouse Gas Regulations
Emissions Standards for Vehicles and Engines -- For light-duty vehicles, rules establishing standards for 2012-2016 model years and 2017-2025 model years. -- For heavy- and medium-duty trucks, a rule establishing standards for 2014-2018 model years.
Carbon Pollution Standard for New Power Plants -- A proposed rule setting limits on CO_2 emissions from future power plants.
Stationary Source Permitting -- A rule setting greenhouse gas emissions thresholds to define when permits under the New Source Review Prevention of Significant Deterioration and Title V Operating Permit programs are required for new and modified industrial facilities.
Greenhouse Gas Reporting Program -- A program requiring annual reporting of greenhouse gas data from large emission sources and suppliers of products that emit greenhouse gases when released or combusted.
Other Rules and Regulations with Climate Co-Benefits
Oil and Natural Gas Air Pollution Standards -- A rule revising New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants for certain components of the oil and natural gas industry.
Mobile Source Control Programs -- Particle control regulations affecting mobile sources (especially diesel engines) that reduce black carbon by controlling direct particle emissions. -- The requirement to blend increasing volumes of renewable fuels.
National Forest Planning -- Identification and evaluation of information relevant to a baseline assessment of carbon stocks. -- Reporting of net carbon stock changes on forestland.
Standards and Subsidies
Appliance and Building Efficiency Standards -- Energy efficiency standards and test procedures for residential, commercial, industrial, lighting, and plumbing products. -- Model residential and commercial building energy codes, and technical assistance to state and local governments, and non-governmental organizations.
Financial Incentives for Efficiency and Alternative Fuels and Technology -- Weatherization assistance for low-income households, tax incentives for commercial and residential buildings and efficient appliances, and support for state and local efficiency programs. -- Tax credits for biodiesel and advanced biofuel production, alternative fuel infrastructure, and purchase of electric vehicles. -- Loan guarantees for innovative energy or advanced technology vehicle production and manufacturing; investment and production tax credits for renewable energy.
Funding of Research, Development, Demonstration, and Deployment
-- Programs on clean fuels, energy end-use and infrastructure, CO_2 capture and storage, and agricultural practices.
Federal Agency Practices and Procurement
-- Executive orders and federal statutes requiring federal agencies to reduce building energy and resource consumption intensity and to procure alternative fuel vehicles. -- Agency-initiated programs in most departments oriented to lowering energy use and greenhouse gas emissions.

Table 27.2. Most states and Native communities have implemented programs to reduce greenhouse gases or adopt increased energy efficiency goals.

State Climate and Energy Initiatives
Examples of greenhouse gas policies include:
Greenhouse Gas Reporting and Registries http://www.c2es.org/us-states-regions/policy-maps/ghg-reporting[65]
Greenhouse Gas Emissions Targets http://www.c2es.org/us-states-regions/policy-maps/emissions-targets[66]
CO_2 Controls on Electric Power plants http://www.edf.org/sites/default/files/state-ghg-standards-03132012.pdf[67]
Low-Carbon Fuel Standards http://www.c2es.org/us-states-regions/policy-maps/low-carbon-fuel-standard[68]
Climate Action Plans http://www.c2es.org/us-states-regions/policy-maps/action-plan[69]
Cap and Trade Programs http://arb.ca.gov/cc/capandtrade/capandtrade.htm[70]
Regional Agreements http://www.c2es.org/us-states-regions/regional-climate-initiatives#WCI[71]
Tribal Communities http://www.epa.gov/statelocalclimate/tribal[72]
States have also taken a number of energy measures, motivated in part by greenhouse gas concerns. For example: Renewable Portfolio Standards http://www.dsireusa.org/documents/summarymaps/RPS_map.pdf[73]
Energy Efficiency Resource Standards http://www.dsireusa.org/documents/summarymaps/EERS_map.pdf[74]
Property Tax Incentives for Renewables http://www.dsireusa.org/documents/summarymaps/[75]

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
Evaluation of literature by Coordinating Lead Authors

Key message #1 Traceable Account

Carbon dioxide is removed from the atmosphere by natural processes at a rate that is roughly half of the current rate of emissions from human activities. Therefore, mitigation efforts that only stabilize global emissions will not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase. The same is true for other long-lived greenhouse gases.

Description of evidence base
The message is a restatement of conclusions derived from the peer-reviewed literature over nearly the past 20 years (see Section 1 of chapter). Publications have documented the long lifetime of CO_2 in the atmosphere, resulting in long time lags between action and reduction,[9,11,76] and Earth System Models have shown that stabilizing emissions will not immediately stabilize atmospheric concentrations, which will continue to increase.[4]

New information and remaining uncertainties
There are several important uncertainties in the current carbon cycle, especially the overall size, location, and dynamics of the land-use sink[9,11] and technological development and performance.

Simulating future atmospheric concentrations of greenhouse gases requires both assumptions about economic activity, stringency of any greenhouse gas emissions control, and availability of technologies, as well as a number of assumptions about how the changing climate system affects both natural and anthropogenic sources.

Assessment of confidence based on evidence
Very High. Observations of changes in the concentrations of greenhouse gases are consistent with our understanding of the broad relationships between emissions and concentrations.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

To meet the lower emissions scenario (B1) used in this assessment, global mitigation actions would need to limit global carbon dioxide emissions to a peak of around 44 billion tons per year within the next 25 years and decline thereafter. In 2011, global emissions were around 34 billion tons, and have been rising by about 0.9 billion tons per year for the past decade. Therefore, the world is on a path to exceed 44 billion tons per year within a decade.

Description of evidence base
A large number of emissions scenarios have been modeled, with a number of publications showing what would be required to limit CO_2[13,53,54,77] to any predetermined limit. At current concentrations and rate of rise, the emissions of CO_2 would need to peak around

44 billion tons within the next 25 years in order to stabilize concentrations as in the B1 scenario. Given the rate of increase in recent years,[10] this limit is expected to be surpassed.[78]

New information and remaining uncertainties

Uncertainties about the carbon cycle could affect these calculations, but the largest uncertainties are the assumptions made about the strength and cost of greenhouse gas emissions policies.

Assessment of confidence based on evidence

The confidence in the conclusion is **high**. This is a contingent conclusion, though – we do not have high confidence that the current emission rate will be sustained. However, we do have high confidence that if we do choose to limit concentrations as in the B1 scenario, emissions will need to peak soon and then decline.

Key message #3 Traceable Account

Over recent decades, the U.S. economy has emitted a decreasing amount of carbon dioxide per dollar of gross domestic product. Between 2008 and 2012, there was also a decline in the total amount of carbon dioxide emitted annually from energy use in the United States as a result of a variety of factors, including changes in the economy, the development of new energy production technologies, and various government policies.

Description of evidence base

Trends in greenhouse gas emissions intensity are analyzed and published by governmental reporting agencies.[20,23,26] Published, peer-reviewed literature cited in Section 2 of the Mitigation Chapter supports the conclusions about why these trends have occurred.[79]

New information and remaining uncertainties

Economic and technological forecasts are highly uncertain.

Assessment of confidence based on evidence

High. The statement is a summary restatement of published analyses by government agencies and interpretation from the reviewed literature.

Key message #4 Traceable Account

Carbon storage in land ecosystems, especially forests, has offset around 17% of annual U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" may not be sustainable.

Description of evidence base

Underlying data come primarily from U.S. Forest Service Forest Inventory and Analysis (FIA) plots, supplemented by additional ecological data collection efforts. Modeling conclusions come from peer-reviewed literature. All references are in Section 2 of the Mitigation Chapter. Studies have shown that there is a large land-use carbon sink in the United States.[26,27,28] Many publications attribute this sink to forest re-growth, and the sink is projected to decline as a result of forest aging[30,31,33] and factors like drought, fire, and insect infestations[31] reducing the carbon sink of these regions.

New information and remaining uncertainties

FIA plots are measured extremely carefully over long time periods, but do not cover all U.S. forested land. Other U.S. land types must have carbon content estimated from other sources. Modeling relationships between growth and carbon content, and taking CO_2 and climate change into account have large scientific uncertainties associated with them.

Assessment of confidence based on evidence

High. Evidence of past trends is based primarily on government data sources, but these also have to be augmented by other data and models in order to incorporate additional land-use types. Projecting future carbon content is consistent with published models, but these have intrinsic uncertainties associated with them.

Key message #5 Traceable Account

Both voluntary activities and a variety of policies and measures that lower emissions are currently in place at federal, state, and local levels in the United States, even though there is no comprehensive national climate legislation. Over the remainder of this century, aggressive and sustained greenhouse gas emission reductions by the United States and by other nations would be needed to reduce global emissions to a level consistent with the lower scenario (B1) analyzed in this assessment.

Description of evidence base

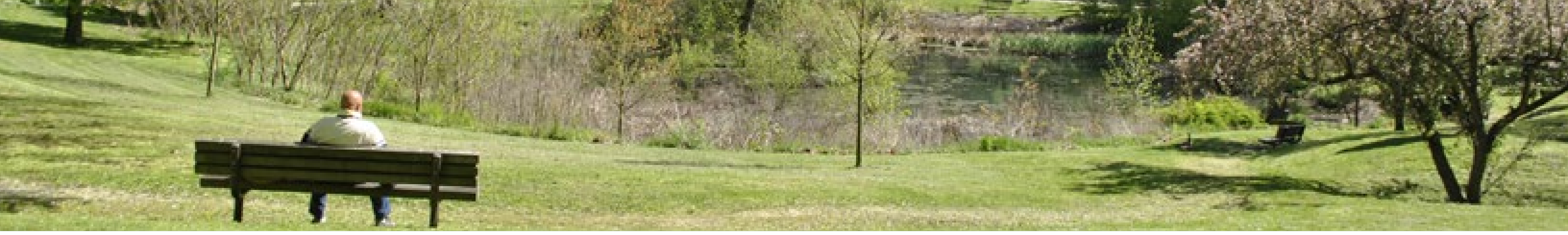
The identification of state, local, regional, federal, and voluntary programs that will have an effect of reducing greenhouse gas emissions is a straightforward accounting of both legislative action and announcements of the implementation of such programs. Some of the programs include the Carbon Disclosure Project (CDP), the American College and University Presidents' Climate Commitment (ACUPCC), U.S. Mayors Climate Protection Agreement,[39] and many other local government initiatives.[38] Several states have also adapted climate policies including California's Global Warming Solutions Act (AB 32) and the Regional Greenhouse Gas Initiative (RGGI). The assertion that they will not lead to a reduction of US CO_2 emissions is supported by calculations from the U.S. Energy Information Administration.

New information and remaining uncertainties

The major uncertainty in the calculation about future emissions levels is whether a comprehensive national policy will be implemented.

Assessment of confidence based on evidence

Very High. There is recognition that the implementation of voluntary programs may differ from how they are originally planned, and that institutions can always choose to leave voluntary programs (as is happening with RGGI, noted in the chapter). The statement about the future of U.S. CO_2 emissions cannot be taken as a prediction of what will happen – it is a conditional statement based on an assumption of no comprehensive national legislation or regulation.



CHAPTER 28
ADAPTATION

Convening Lead Authors

Rosina Bierbaum, University of Michigan

Arthur Lee, Chevron Corporation

Joel Smith, Stratus Consulting

Lead Authors

Maria Blair, Independent

Lynne M. Carter, Louisiana State University

F. Stuart Chapin III, University of Alaska Fairbanks

Paul Fleming, Seattle Public Utilities

Susan Ruffo, The Nature Conservancy

Contributing Authors

Shannon McNeeley, Colorado State University

Missy Stults, University of Michigan

Laura Verduzco, Chevron Corporation

Emily Seyller, University Corporation for Atmospheric Research

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On the Web http://nca2014.globalchange.gov/report/response-strategies/adaptation

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

28 ADAPTATION

Key Messages

1. **Substantial adaptation planning is occurring in the public and private sectors and at all levels of government; however, few measures have been implemented and those that have appear to be incremental changes.**

2. **Barriers to implementation of adaptation include limited funding, policy and legal impediments, and difficulty in anticipating climate-related changes at local scales.**

3. **There is no "one-size fits all" adaptation, but there are similarities in approaches across regions and sectors. Sharing best practices, learning by doing, and iterative and collaborative processes including stakeholder involvement, can help support progress.**

4. **Climate change adaptation actions often fulfill other societal goals, such as sustainable development, disaster risk reduction, or improvements in quality of life, and can therefore be incorporated into existing decision-making processes.**

5. **Vulnerability to climate change is exacerbated by other stresses such as pollution, habitat fragmentation, and poverty. Adaptation to multiple stresses requires assessment of the composite threats as well as tradeoffs among costs, benefits, and risks of available options.**

6. **The effectiveness of climate change adaptation has seldom been evaluated, because actions have only recently been initiated and comprehensive evaluation metrics do not yet exist.**

Over the past few years, the focus moved from the question "Is climate changing?" to the equally important question: "Can society manage unavoidable changes and avoid unmanageable changes?"[1,2] Research demonstrates that both mitigation (efforts to reduce future climate changes) and adaptation (efforts to reduce the vulnerability of society to climate change impacts) are needed in order to minimize the damages from human-caused climate change and to adapt to the pace and ultimate magnitude of changes that will occur.[3,4,5]

Adaptation and mitigation are closely linked; adaptation efforts will be more difficult, more costly, and less likely to succeed if significant mitigation actions are not taken.[2,6] The study and application of adaptation in the climate change realm is nascent compared to the many analyses of mitigation policies and practices to reduce emissions. Uncertainties about future socioeconomic conditions as well as future climate changes can make it difficult to arrive at adaptation decisions now. However, the pace and magnitude of projected change emphasize the need to be prepared for a wide range and intensity of climate impacts in the future. Planning and managing based on the climate of the last century means that tolerances of some infrastructure and species will be exceeded.[5,7,8] For example, building codes and landscaping ordinances will likely need to be updated not only for energy efficiency but also to conserve water supplies, protect against disease vectors, reduce susceptibility to heat stress, and improve protection against extreme events.[5,9] Although there is uncertainty about future conditions, research indicates that intelligent adaptive actions can still be taken now.[10,11] Climate change projections have inherent uncertainties, but it is still important to develop, refine, and deploy tools and approaches that enable iterative decision-making and increase flexibility and robustness of climate change responses (Ch. 2: Our Changing Climate).[12]

Climate change affects human health, natural ecosystems, built environments, and existing social, institutional, and legal arrangements. Adaptation considerations include local, state, regional, national, and international issues. For example, the implications of international arrangements need to be considered in the context of managing the Great Lakes, the Columbia River, and the Colorado River to deal with drought.[13,14] Both "bottom up" community planning and "top down" national strategies[11] may help regions deal with impacts such as increases in electrical brownouts, heat stress, floods, and wildfires. Such a mix of approaches will require cross-boundary coordination at multiple levels as operational agencies integrate adaptation planning into their programs.

Adaptation actions can be implemented reactively, after changes in climate occur, or proactively, to prepare for projected changes.[11] Proactively preparing can reduce the harm from certain climate change impacts, such as increasingly intense extreme events, shifting zones for agricultural crops, and rising sea levels, while also facilitating a more rapid and efficient response to changes as they happen. This chapter highlights efforts at the federal, regional, state, tribal, and local levels, as well as initiatives in the corporate and non-governmental sectors to build adaptive capacity and resilience in response to climate change. While societal adaptation to *climate variability* is as old as civilization itself,[15] the focus of this chapter is on preparing for unprecedented human-induced *climate change* through adaptation. A map of illustrative adaptation activities and four detailed case examples that highlight ongoing adaptation activity across the U.S. are provided in Section 4 of this chapter.

Adaptation key terms definitions*

Adapt, Adaptation: Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.

Adaptive Capacity: The potential of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, take advantage of opportunities, and cope with the consequences.

Mitigation: Technological change and substitutions that reduce resource inputs and emissions per unit of output. Although several social, economic, and technological actions would reduce emissions, with respect to climate change, mitigation means implementing actions to reduce greenhouse gas emissions or increase the amount of carbon dioxide absorbed and stored by natural and man-made carbon sinks (see Ch. 27: Mitigation).

Multiple Stressors: Stress that originates from different sources that affect natural, managed, and socioeconomic systems and can cause impacts that are compounded and sometimes unexpected. An example would be when economic or market stress combines with drought to negatively impact farmers.

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Risk: A combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

*Definitions adapted from (IPCC 2007; [16] NRC 2007,[17] 2010[11]).

Adaptation Activities in the United States

Federal Government

Federal leadership, guidance, information, and support are vital to planning for and implementing adaptation actions at all scales and in all affected sectors of society (Table 28.1).[11,18,19,20] Several new federal climate adaptation initiatives and strategies have been developed in recent years, including:

- Executive Order (EO) 13514, requiring federal agencies to develop recommendations for strengthening policies and programs to adapt to the impacts of climate change;[21]
- the release of President Obama's Climate Action Plan in June 2013, which has as one of its three major pillars, preparing the United States for the impacts of climate change, including building stronger and safer communities and infrastructure, protecting the economy and natural resources, and using sound science to manage climate impacts;[22]
- the creation of an Interagency Climate Change Adaptation Task Force (ICCATF) (now the Council on Climate Preparedness and Resilience, per Executive Order 13653[23]) that led to the development of national principles for adaptation and

is leading to crosscutting and government-wide adaptation policies;

- the development of three crosscutting national adaptation strategies focused on integrating federal, and often state, local, and tribal efforts on adaptation in key sectors: 1) the National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate;[24] 2) the National Fish, Wildlife and Plants Climate Adaptation Strategy;[25] and 3) a priority objective on resilience and adaptation in the National Ocean Policy Implementation Plan;[26]

- a new decadal National Global Change Research Plan (2012–2021) that includes elements related to climate adaptation, such as improving basic science, informing decisions, improving assessments, and communicating with and educating the public;[27]

- the development of several interagency and agency-specific groups focused on adaptation, including a "community of practice" for federal agencies that are developing and implementing adaptation plans, an Adaptation Science Workgroup inside the U.S. Global Change Research Program (USGCRP), and several agency specific climate change and adaptation task forces; and

- a November 2013 Executive Order entitled "Preparing the United States for the Impacts of Climate Change" that, among other things, calls for the modernizing of federal programs to support climate resilient investments, managing lands and waters for climate preparedness and resilience, the creation of a Council on Climate Preparedness and Resilience, and the creation of a State, Local, and Tribal Leaders Task Force on Climate Preparedness and Resilience.[23]

Federal agencies are all required to plan for adaptation. Actions include coordinated efforts at the White House, regional and cross-sector efforts, agency-specific adaptation plans, as well as support for local-level adaptation planning and action. Table 28.1 lists examples, but is not intended as a comprehensive list.

Table 28.1. Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales*

Agency	Component	Action	Description
All Federal Agencies		Developed Adaptation Plans as part of their annual Strategic Sustainability Performance Plans	The 2012 Strategic Sustainability Performance Plans for Federal agencies contain specific sections on adaptation. Agencies are required to evaluate climate risks and vulnerabilities to manage both short- and long-term effects on missions and operations.
Department of Health and Human Services (HHS)	Centers for Disease Control and Prevention (CDC)	Climate-Ready States and Cities Initiative	Through their first climate change cooperative agreements in 2010, CDC awarded $5.25 million to ten state and local health departments to assess risks and develop programs to address climate change related challenges.
Department of Agriculture (USDA)		Integrating climate change objectives into plans and networks	USDA is using existing networks such as the Cooperative Extension Service, the Natural Resource Conservation Districts, and the Forest Service's Climate Change Resource Center to provide climate services to rural and agricultural stakeholders.
USDA	Forest Service	Developed a *National Roadmap for Responding to Climate Change* and a *Guidebook for Developing Adaptation Options*, among many resources	The *National Roadmap* was developed in 2010 to identify short- and long-term actions to reduce climate change risks to the nation's forests and grasslands. The *Guidebook* builds on this previous work and provides science-based strategic and tactical approaches to adaptation.
Department of Commerce (DOC)	NOAA	Supporting research teams and local communities on adaptation-related issues and develops tools and resources	Through the Regional Integrated Sciences and Assessments (RISAs) program, develop collaboration between researchers and managers to better manage climate risks. Through the Regional Climate Centers (RCCs) and the Digital Coast partnership, deliver science to support decision-making.
Department of Defense (DoD)		Developed a DoD Climate Change Adaptation Roadmap	DoD released its initial Department-level Climate Change Adaptation Roadmap in 2012. The Roadmap identifies four goals that serve as the foundation for guiding the Department's response to climate change that include using a robust decision making approach based on the best available science.

Table 28.1. Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales* (Continued)

DoD	U.S. Army Corps of Engineers (USACE), Civil Works Program	Developed climate change adaptation plan; making progress in priority areas including vulnerability assessments and development of policy and guidance	The USACE Civil Works Program initial climate change adaptation plan in 2011 has a goal to reduce vulnerabilities and improve resilience of water resources infrastructure impacted by climate change. Vulnerability assessments and pilot projects are in progress. Other guidance is underway.
DoD	Department of the Navy	Developed road maps for adaptation in the Arctic and across the globe	The Navy Arctic Roadmap (November 2009) promotes maritime security and naval readiness in a changing Arctic. The Climate Change Roadmap (May 2010) examines broader issues of climate change impacts on Navy missions and capabilities globally.
Department of Energy (DOE)		Develop higher spatial and temporal scales of climate projections and integrate adaptation and climate considerations into integrated assessments	Develops community-based, high-resolution (temporal and spatial) models for climate projections and integrated assessment models that increasingly reflect multi-sectoral processes and interactions, multiple stressors, coupled impacts, and adaptation potential.
DOE		Developed climate change adaptation plan, and completed comprehensive study of vulnerabilities to the energy sector of climate change and extreme weather	The 2013 DOE Report "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather" examines current and potential future impacts of climate trends and identifies activities underway and potential opportunities to enhance energy system climate preparedness and resilience.
Department of Homeland Security (DHS)	Federal Emergency Management Agency (FEMA)	Works with communities across the Nation to help them prioritize their activities to reduce risks	FEMA released a Climate Change Adaptation Policy Statement establishing the Agency's approach to supporting the Department in ensuring resilience to disasters in the face of climate change. FEMA's action areas focus on developing actionable "future risk" tools, enabling state and local adaptation, and building resilience capabilities.
Department of the Interior (DOI)	Fish and Wildlife Service (FWS)	Developed a FWS climate change strategic plan (2010) and established a network of Landscape Conservation Cooperatives (LCCs)	Established a framework to help ensure the sustainability of fish, wildlife, plants, and habitats in the face of climate change. Created a network of 22 LCCs to promote shared conservation goals, approaches, and resource management planning and implementation across the United States.
DOI	U.S. Geological Survey (USGS)	Established a network of Climate Science Centers (CSCs)	DOI operates a National Climate Change and Wildlife Center and eight regional CSCs, which provide scientific information and tools that land, water, wildlife, and cultural resource managers and other stakeholders can apply to anticipate, monitor, and adapt to climate change.
DOI	National Park Service (NPS)	Climate Change Response Strategy (2010), Climate Change Action Plan (2012), and Green Parks Plan (2012)	NPS actions span climate change science, adaptation, mitigation, and communication across national parks, including exhibits for park visitors, providing climate trend information for all national parks, risk screening and adaptation for coastal park units, and implementing scenario planning tools.
DOI	Bureau of Land Management (BLM)	Rapid Ecoregional Assessments (REAs)	REAs synthesize information about resource conditions and trends within an ecoregion; assess impacts of climate change and other stressors; map areas best-suited for future development; and establish baseline environmental conditions, against which to gauge management effectiveness.

Table 28.1. Examples of Individual Federal Agency Actions to Promote, Implement, and Support Adaptation at Multiple Scales* (Continued)

Department of Transportation (DOT)	Federal Highway Administration (FHWA)	Developed Risk Assessment Model for transportation decisions	DOT worked with five local and state transportation authorities to develop a conceptual Risk Assessment Model to identify which assets are: a) most exposed to climate change threats and/or b) associated with the most serious potential consequences of climate change threats. Completed November 2011.
DOT		Comprehensive study of climate risks to Gulf Coast transportation infrastructure followed by in-depth study of Mobile, AL	Phase 1 of the 2008 study assessed transportation infrastructure vulnerability to climate change impacts across the Gulf. Phase 2, to be completed in 2013, focuses on Mobile, AL. This effort will develop transferable tools for transportation planners.
Environmental Protection Agency (EPA)		Established the Climate Ready Estuaries program, the Climate Ready Water Utilities initiative, and a tribal climate change adaptation planning training program	These selected EPA initiatives provide resources and tools to build the capacity of coastal managers, water utilities, and tribal environmental professionals to plan for and implement adaptation strategies.
National Aeronautics and Space Administration (NASA)		Initiated NASA's Climate Adaptation Science Investigator (CASI) Workgroup to partner NASA scientists, engineers, and institutional stewards	The CASI team builds capacity to address climate change at NASA facilities by downscaling facility-specific climate hazard information and projections; conducting customized climate research for each location; and leading resilience and adaptation workshops that spur community-based responses.

*Material provided in table is derived directly from Agency representatives and Agency websites. These are select examples and should not be considered all-inclusive.

Federal agencies can be particularly helpful in facilitating climate adaptation by:

- fostering the stewardship of public resources and maintenance of federal facilities, services, and operations such as defense, emergency management, transportation, and ecosystem conservation in the face of a changing climate;[11,28,29,30]
- providing usable information and financial support for adaptation;[11,20,30]
- facilitating the dissemination of best practices and supporting a clearinghouse to share data, resources, and lessons learned;[11,20,31]
- dealing with and anticipating impacts that cross geopolitical boundaries, assisting in disaster response, and supporting flexible regulatory frameworks;[11,30]
- ensuring the establishment of federal policies that allow for "flexible" adaptation efforts and take steps to avoid unintended consequences;[30,32] and
- building public awareness.[33]

States

States have become important actors in national climate change related efforts. State governments can create policies and programs that encourage or discourage adaptation at other governance scales (such as counties or regions)[34] through regulation and by serving as laboratories for innovation.[35,36] Although many of these actions are not specifically designed to address climate change, they often include climate adaptation components.

Many state-level climate change-specific adaptation actions focus on planning. As of 2013, fifteen states had completed climate adaptation plans; four states were in the process of writing their plans; and seven states had made recommendations to create state-wide adaptation plans.[37]

In addition to formal adaptation plans, numerous states have created sector-specific plans that consider long-term climate change (Figure 28.1). For example, at least 16 states have biodiversity conservation plans that focus on preparing for long-term changes in climate.[38] In addition to planning, some states have created legislation and/or programs that are either directly or indirectly targeted at reducing climate vulnerabilities (Table 28.2).

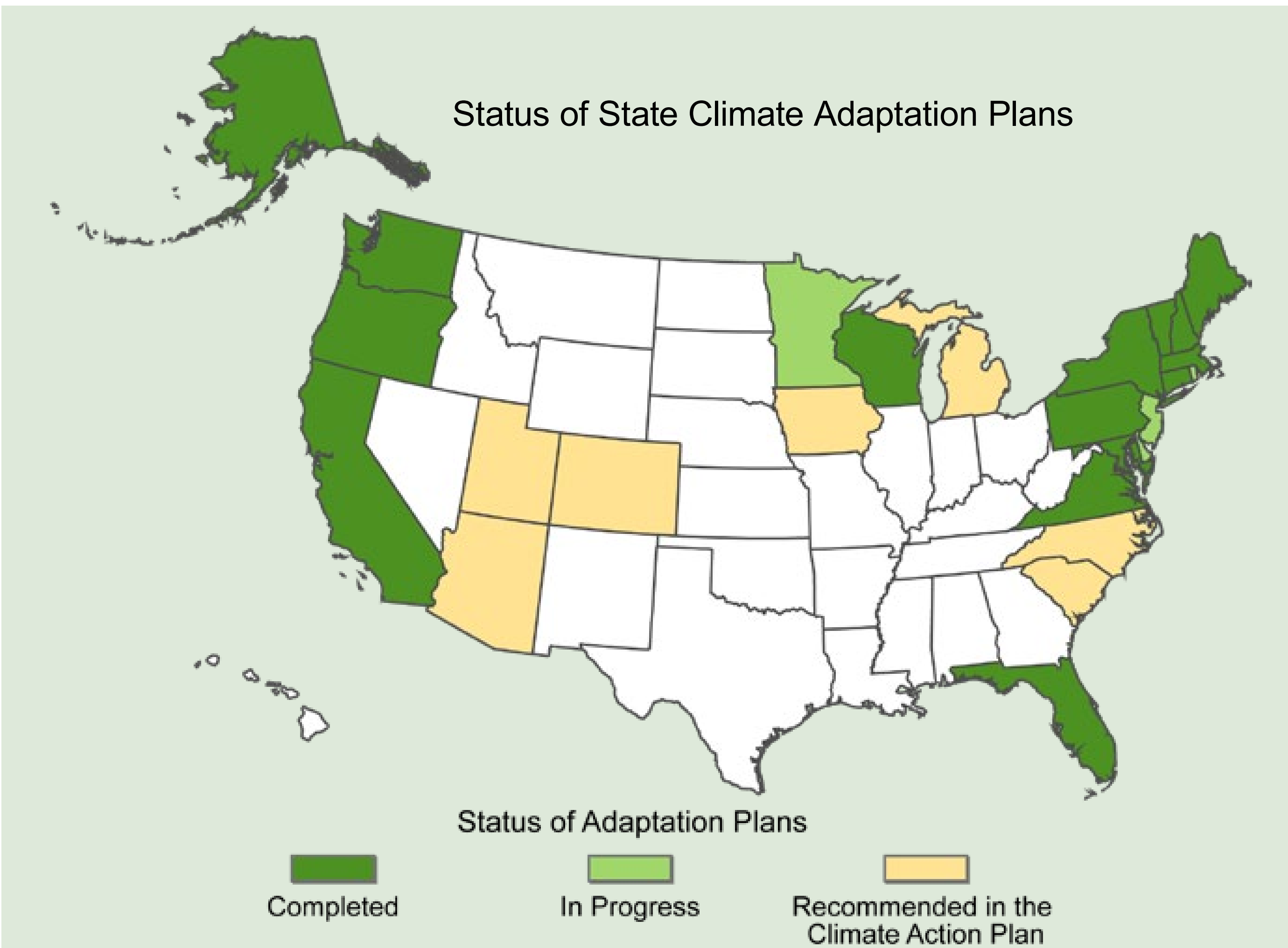


Figure 28.1. Status of State Climate Adaptation Plans. (Figure source: redrawn from C2ES 2013[37]).

Table 28.2. Examples of State-Level Adaptation Activities*

State	Adaptation Action
Alaska	Alaska Climate Change Impact Mitigation Program provides funds for hazard impact assessments to evaluate climate change related impacts, such as coastal erosion and thawing permafrost.[39]
California	Building standards mandating energy and water efficiency savings, advancing both adaptation and mitigation; State Adaptation Plan calls for 20% reduction in per capita water use.[40]
Florida	Law supporting low water use landscaping techniques.[41]
Hawaii	Water code that calls for integrated management, preservation, and enhancement of natural systems.[42]
Kentucky	*Action Plan to Respond to Climate Change in Kentucky: A Strategy of Resilience,* which identifies six goals to protect ecosystems and species in a changing climate.[43]
Louisiana	*Comprehensive Master Plan for a Sustainable Coast 2012* includes both protection and restoration activities addressing land loss from sea level rise, subsidence, and other factors over the next 50 years.[44]
Maine	The *Maine Sand Dune Rules* require that structures greater than 2,500 square feet be set back at a distance that is calculated based on the future shoreline position and considering two feet of sea level rise over the next 100 years.[45]
Maryland	Passed *Living Shorelines Act* to reduce hardened shorelines throughout the state;[46] passed "Building Resilience to Climate Change" policy which establishes practices and procedures related to facility siting and design, new land investments, habitat restoration, government operations, research and monitoring, resource planning, and advocacy.
Montana	Maintains a statewide climate change website to help stakeholders access relevant and timely climate information, tools, and resources.
New Mexico	The Active Water Resource Management program allows for temporary water rights changes in real time in case of drought.[47]
Pennsylvania	Enacted polices to encourage the use of green infrastructure and ecosystem-based approaches for managing storm water and flooding.[9]
Rhode Island	Requires public agencies considering land-use applications to accommodate a 3- to 5-foot rise in sea level.
Texas	Coordinated response to drought through National Integrated Drought Information System (NIDIS); RISAs (Southern Climate Impacts Planning Program [SCIPP], Climate Assessment for the Southwest [CLIMAS]); and state and private sector partners through anticipatory planning and preparedness (for example, implemented in 2011 drought).[48]

*This list contains selected examples of state-level adaptation activities and should not be considered all-inclusive.

Tribal Governments

Tribal governments have been particularly active in assessing and preparing for the impacts of climate change (see Ch. 12: Indigenous Peoples). For example:

- Adaptation planning in Point Hope, Alaska, emphasizes strategies for enhancing community health.[49]
- In Newtok, Alaska, the village council is leading a land-acquisition and planning effort to relocate the community, because climate change induced coastal erosion has destroyed essential infrastructure, making the current village site unsafe.[50]
- The Tulalip Tribes in Washington State are using traditional knowledge gleaned from elders, stories, and songs and combining this knowledge with downscaled climate data to inform decision-making.[51] Also in Washington State, the Swinomish Indian Tribal Community integrated climate change into decision-making in major sectors of the Swinomish Community, such as education, fisheries, social services, and human health.[52]
- The Haudenosaunee Confederacy in the northeastern U.S. is addressing climate impacts by preserving a native food base through seed-banking (Ch. 12: Indigenous Peoples).[51]

Local and Regional Governments

Most adaptation efforts to date have occurred at local and regional levels.[53,54,55,56,57] Primary mechanisms that local governments are using to prepare for climate change include land-use planning; provisions to protect infrastructure and ecosystems; regulations related to the design and construction of buildings, roads, and bridges; and emergency preparation, response, and recovery (Table 28.3).[9,45,56,58]

According to a recent survey of 298 U.S. local governments, 59% indicated they are engaged in some form of adaptation planning.[59] Local adaptation planning and actions are unfolding in municipalities of varying sizes and in diverse geographical areas. Communities such as Keene, New Hampshire; New York City, New York; King County, Washington; and Chicago, Illinois are vanguards in the creation of climate adaptation strategies.[9,11,60] In addition to local government action, regional agencies and regional aggregations of governments are becoming significant climate change adaptation actors.[8,57]

Table 28.3. Examples of Local and Regional Adaptation Activities*

Local or Regional Government	Adaptation Action
Satellite Beach, FL	Collaboration with the Indian River Lagoon National Estuary Program led to efforts to try to incorporate sea level rise projections and policies into the city's comprehensive growth management plan.[54]
Portland, OR	Updated the city code to require on-site stormwater management for new development and re-development. Provides a downspout disconnection program to help promote on-site stormwater management .[61]
Lewes, DE	In partnership with Delaware Sea Grant, ICLEI-Local Governments for Sustainability, the University of Delaware, and state and regional partners, the City of Lewes undertook a stakeholder-driven process to understand how climate adaptation could be integrated into the hazard mitigation planning process. Recommendations for integration and operational changes were adopted by the City Council and are currently being implemented.[62]
Groton, CT	Partnered with federal, state, regional, local, non-governmental, and academic partners through the EPA's Climate Ready Estuaries program to assess vulnerability to and devise solutions for sea level rise.[63]
San Diego Bay, CA	Five municipalities partnered with the port, the airport, and more than 30 organizations with direct interests in the Bay's future to develop the San Diego Bay Sea Level Rise Adaptation Strategy. The strategy identified key vulnerabilities for the Bay and adaptation actions that can be taken by individual agencies, as well as through regional collaboration.[9]
Chicago, IL	Through a number of development projects, the city has added 55 acres of permeable surfaces since 2008 and has more than four million square feet of green roofs planned or completed.[64]
King County, WA	Created King County Flood Control District in 2007 to address increased impacts from flooding through activities such as maintaining and repairing levees and revetments, acquiring repetitive loss properties, and improving countywide flood warnings.[65]
New York City, NY	Through a partnership with the Federal Emergency Management Agency (FEMA), the city is updating FEMA Flood Insurance Rate Maps based on more precise elevation data. The new maps will help stakeholders better understand their current flood risks and allow the city to more effectively plan for climate change.[66]
Southeast Florida Climate Change Compact	Joint commitment among Broward, Miami-Dade, Palm Beach, and Monroe Counties to partner in reducing heat-trapping gas emissions and adapting to climate impacts, including adaptation in transportation, water resources, natural resources, agriculture, and disaster risk reduction. Notable policies emerging from the Compact include regional collaboration to revise building codes and land development regulations to discourage new development or post-disaster redevelopment in vulnerable areas.[67]
Phoenix, AZ; Boston, MA; Philadelphia, PA; and New York, NY	Climate change impacts are being integrated into public health planning and implementation activities that include creating more community cooling centers, neighborhood watch programs, and reductions in the urban heat island effect.[9,68,69]
Boulder, CO; New York, NY; and Seattle, WA	Water utilities in these communities are using climate information to assess vulnerability and inform decision-making.[61]
City of Philadelphia	In 2006, the Philadelphia Water Department began a program to develop a green stormwater infrastructure, intended to convert more than one-third of the city's impervious land cover to "Greened Acres": green facilities, green streets, green open spaces, green homes, etc., along with stream corridor restoration and preservation.[5]

*This table includes select examples of local and regional adaptation activities and should not be considered all-inclusive.

There is no one-size-fits-all adaptation solution to the challenges of adapting to climate change impacts, as solutions will differ depending on context, local circumstance, and scale as well as on local culture and internal capacity.[9,31]

Non-governmental and Private Sector

Many non-governmental entities have been significant actors in the national effort to prepare for climate change by providing assistance that includes planning guidance, implementation tools, contextualized climate information, best practice exchange, and help with bridging the science-policy divide to a wide array of stakeholders (Table 28.4).[70,71] The Nature Conservancy, for example, established the Canyonlands Research Center in Monticello, Utah, to facilitate research and develop conservation applications for resource issues under the multi-stresses of climate change and land-use demands in the Colorado Plateau region.[72]

This one-acre stormwater wetland was constructed in Philadelphia to treat stormwater runoff in an effort to improve drinking water quality while minimizing the impacts of storm-related flows on natural ecosystems.

With regard to the private sector, evidence from organizations such as the Carbon Disclosure Project (CDP) and the Securities and Exchange Commission's (SEC) Climate Change 10-K Disclosure indicate that a growing number of companies are beginning to actively address risks from climate change (Table 28.5).[73] The World Business Council for Sustainable Development (WBCSD) and the Center for Climate and Energy Solutions (C2ES) have identified three types of risks driving private sector adaptation efforts, including risks to core operations, the value chain, and broader changes in the economy and infrastructure (see Figure 28.2).[74,75,76]

This analysis is supported by responses to the 2011 CDP, and suggests that companies are concerned about how changes in the climate will impact issues such as feedstock, water supply and quality, infrastructure, core operations, supply chains, and customers' ability to use (and their need for) services.[73]

Some companies are taking action to not only avoid risk, but to explore potential opportunities that may emerge in a changing climate, such as developing new products and services, developing or expanding existing consulting services, expanding into new operational territories, extending growing seasons and hours of operation, and responding to increased demand for existing products and services.[73,75,77,78]

Table 28.4. Examples of Non-governmental Adaptation Efforts and Services*

Types of Adaptation Efforts and Services	Examples of Organizations Providing Services
Adaptation planning assistance, including creation of guides, tools, and templates	Center for Climate Strategies, ICLEI-Local Governments for Sustainability, International Institute for Sustainable Development, Natural Resources Defense Council, The Nature Conservancy, World Resources Institute, World Wildlife Fund
Networking and best practice exchange	C40 Cities Climate Leadership Group, Adaptation Network, Center for Clean Air Policy, Climate Adaptation Knowledge Exchange, ICLEI-Local Governments for Sustainability, Institute for Sustainable Communities, Urban Sustainability Directors Network, World Business Council for Sustainable Development
Climate information providers	Union of Concerned Scientists, Urban Climate Change Research Network, Stockholm Environment Institute–U.S. Center
Policy, legal, and institutional support	Center for Climate and Energy Solutions (formerly Pew Center on Global Climate Change), Georgetown Climate Center
Aggregation of adaptation-pertinent information	Carbon Disclosure Project, Climate Adaptation Knowledge Exchange, Georgetown Climate Center

*This list contains examples of non-governmental organizations providing the identified services and should not be considered all-inclusive or a validation of actions claimed by the organizations.

Table 28.5. Examples of Private Sector Actions to Adapt to Climate Risks as Reported to the Carbon Disclosure Project*

Company	Sector	Climate Risk	Examples of Actions Undertaken
Coca-Cola Company	Consumer Staples	Changes in physical climate parameters; Changes in other climate-related developments	Coca-Cola is working around the world to replenish the water used in finished beverages by participating in locally relevant water projects that support communities and nature. Since 2005, the Coca-Cola system has engaged in more than 320 projects in 86 countries. The range of community projects includes watershed protection; expanding community drinking water and sanitation access; water for productive use, such as agricultural water efficiency; and education and awareness programs. (http://www.thecoca-colacompany.com/citizenship/conservation_partnership.html)
ConAgra Foods, Inc.	Consumer Staples	Company experienced weather-related sourcing challenges, such as delayed tomato harvesting due to unseasonably cool weather, and difficulty sourcing other vegetables due to above normal precipitation.	As part of its business continuity planning, ConAgra Foods has analyzed its supply risk to develop strategic partnerships with suppliers, minimize sole-sourced ingredients, and identify alternate suppliers and contract manufacturers to minimize production disruptions in the instance of an unexpected disruption in supply. (http://company.conagrafoods.com/phoenix.zhtml?c=202310&p=Policies_Environment)
Constellation Brands	Consumer Staples	Changes in physical climate parameters; Changes in other climate-related developments	Constellation has already taken adaptation actions, particularly in California where water availability is an issue, to manage or adapt to these risks. Constellation is working with numerous organizations to help fund industry-based research to determine potential climate change impacts on vineyard production.
Munich Re	Reinsurance	Changes in regulation; Changes in physical climate parameters; Changes in other climate-related developments	Since 2007, a Group-wide climate change strategy covering all aspects of climate change – for example, weather-related impacts, regulatory impacts, litigation and health risks, etc. – has supported their core corporate strategy. The strategy is based on five pillars: mitigation, adaptation, research, in-house carbon dioxide reduction, and advocacy. (http://www.munichre.com/en/group/focus/climate_change/default.aspx)
Pacific Gas and Electric Company (PG&E)	Utilities	Changes in regulation; changes in physical climate parameters; Changes in other climate-related developments	PG&E's adaptation strategies for potential increased electricity demand include expanded customer energy efficiency and demand response programs and improvements to its electric grid. PG&E is proactively tracking and evaluating the potential impacts of reductions to Sierra Nevada snowpack on its hydroelectric system and has developed adaptation strategies to minimize them. Strategies include maintaining higher winter carryover reservoir storage levels, reducing conveyance flows in canals and flumes in response to an increased portion of precipitation falling as rain, and reducing discretionary reservoir water releases during the late spring and summer. PG&E is also working with both the U.S. Geological Survey (USGS) and the California Department of Water Resources to begin using the USGS Precipitation-Runoff Modeling System (PRMS) watershed model, to help manage reservoirs on watersheds experiencing mountain snowpack loss. (http://www.pge.com/about/environment/commitment/)
SC Johnson & Son, Inc.	Household Products	Changes in physical climate parameters	SC Johnson is adjusting to the various physical risks that climate change imposes through a diversified supplier and global manufacturing base. In March 2009, SC Johnson announced a broad ingredient communication program. SC Johnson assesses risks along each ingredient's supply chain to ensure that the company is sourcing from a geographically diverse supplier base. In addition to evaluating product ingredients, SC Johnson has also diversified its operations around the world, allowing it to maintain business continuity in the face of a regional climate change related disruption. (http://www.scjohnson.com/en/commitment/overview.aspx)
Spectra Energy, Inc.	Energy	Changes in regulation; Changes in physical climate parameters; Changes in other climate-related developments	Spectra Energy uses a corporate-wide risk analysis framework to ensure the oversight and management of its four major risk categories: financial, strategic, operational, and legal risks. Physical risks posed by climate change fall within these categories and the company uses risk management committees to ensure that all material risks are identified, evaluated, and managed prior to financial approvals of major projects. (http://www.spectraenergy.com/Sustainability/)

* This list contains examples of private sector actions to adapt to climate risks as reported to the Carbon Disclosure Project and should not be considered all-inclusive or a validation of actions claimed by the organizations.

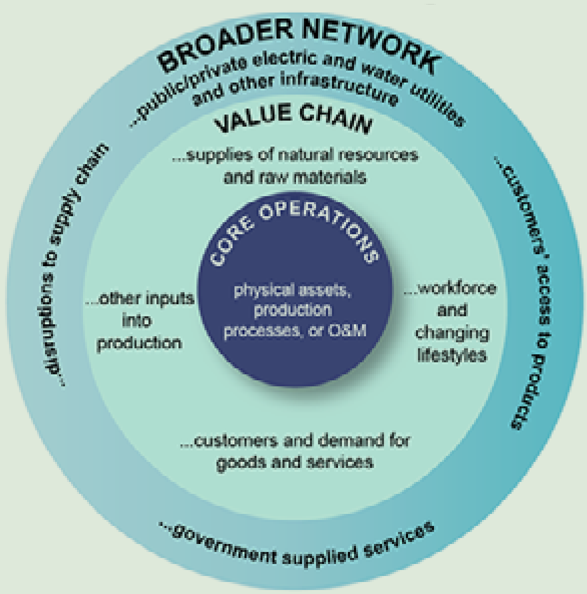


Figure 28.2. "Risk Disk" depicts three pathways by which risks posed by climate change can affect business, such as through core operations, the value chain, and broader changes in the economy and infrastructure. (Figure source: redrawn from C2ES 2008[74]).

Section 1: Adaptation Process

General patterns in adaptation processes are beginning to emerge, with similarities discernible across sectors, systems, and scales.[53,78,79]

Figure 28.3. Generalized Adaptation Process (Figure source: adapted from NRC 2010[11]).

This is not a stepwise or linear process; various stages can be occurring simultaneously, in a different order, or be omitted completely. However, as shown clockwise in Figure 28.3, the process generally involves characterizing vulnerability, developing options, implementing actions, monitoring outcomes, and reevaluating strategies. Each of these is described in more detail below.

Identifying and Understanding Risk, Vulnerabilities, and Opportunities

Most adaptation actions are currently in the initial phase, with many actors focusing on identifying the relevant climate risks and conducting current and future risk and vulnerability assessments of their assets and resources.[8,11,59,80,81,82] In 2011, only 13% of 298 U.S. municipalities surveyed had completed vulnerability or risk assessments, but 42% expected to complete an assessment in the future.[59] At least 21 state fish and wildlife agencies have undertaken climate vulnerability assessments or recently completed an assessment of a particular species, habitat, or both.[38] Multiple qualitative and quantitative methods are used to understand climate vulnerability and risk, including case studies and analogue analyses, scenario analyses, sensitivity analyses, monitoring of key species, and peer information sharing.[8,28,83,84]

Planning, Assessing, and Selecting Options

Once risks and vulnerabilities are understood, the next stage typically involves identifying, evaluating, and selecting options for responding to and managing existing and future changes in the climate.[28] Decision support planning methods and associated tools help to identify flexible and context-relevant adaptation activities for implementation.[11,79] Participatory approaches support the integration of stakeholder perspectives and context-specific information into decision-making.[85,86] This approach can include having community members and governing institutions work collectively to define the problem and design adaptation strategies that are robust while being sensitive to stakeholder values.[86,87] Moreover, regional collaboration has emerged as an effective strategy for defining common approaches to reducing potential threats, selecting metrics for tracking purposes, and creating governance structures to help navigate political challenges.[67,88] As discussed above, a number of government and other organizations have developed plans with identified adaptation options.

Common approaches to adaptation planning include "mainstreaming" or integrating climate adaptation into existing management plans (for example, hazard mitigation, ecosystem conservation, water management, public health, risk contingency, and energy) or developing stand-alone adaptation plans.[68,82,89,90]

Many frameworks, tools, and approaches have emerged to help decision-makers make decisions in light of both uncertainty and the need to achieve multiple societal goals.[7,79] Some of these, however, are specific to particular localities or resources, are not easy to use by the intended audiences, do not adequately evaluate tradeoffs, and require sophisticated knowledge of climate change.[91] In general, these approaches promote options that allow reversibility, preserve future options, can tolerate a variety of impacts, and are flexible, such that mid-course adjustments are possible.[32,92] Among these approaches are Robust Decision Making (RDM), Iterative Risk Management (IRM), Adaptive Management or Co-Management, Portfolio Management, and Scenario Planning (see Ch. 26: Decision Support for more on decision frameworks, processes, and tools).[7,11,28,54,93,94,95,96,97]

Implementation

There is little peer-reviewed literature on adaptation actions, or evaluations of their successes and failures.[11,36,81,98] Many of the documents submitted as part of this Third National Climate Assessment (NCA) process indicate that adaptation actions are being implemented for a variety of reasons. Often, these are undertaken with an aim toward reducing current vulnerabilities to hazards or extreme weather events, such as forest thinning and fuel treatments that reduce fire hazards in national forests or through the diversification of supply chain sourcing in the private sector.[72,73] Additionally, an increasing movement toward mainstreaming climate adaptation concerns into existing processes means that discerning unique climate adaptation activities will be a challenge.[82,99]

Monitoring and Evaluation

There is little literature evaluating the effectiveness of adaptation actions.[9,72,79,86] Evaluation and monitoring efforts, to date, have focused on the creation of process-based rather than outcome-based indicators.[86,90] A number of efforts are underway to create indicators related to climate adaptation,[27] including work by the National Climate Assessment and Development Advisory Committee Indicators Working Group[100] and the U.S. Environmental Protection Agency.[101] Part of monitoring should include accounting for costs of adaptation. To be sure, this may be difficult to account for because of challenges in attribution of climate events to climate change versus climate variability. A few studies summarize projected future costs of adaptation.[102,103]

Revise Strategies/Processes and Information Sharing

Uncertainty about future climate as well as population growth, economic development, response strategies, and other social and demographic issues can stymie climate adaptation activity.[95,104,105] Through iterative processes, however, stakeholders can regularly evaluate the appropriateness of planned and implemented activities and revise them as new information becomes available.[11,28,84] Additionally, the sharing of best practices and lessons learned can be pivotal means to advancing understanding and uptake of climate adaptation activity.[82,86] The use of established information-sharing networks, such as regional climate initiatives, are illustrations of the types of networks that have supported stakeholder adaptation activity to-date.[9,76,79,86]

Section 2: Barriers to Adaptation and Examples of Overcoming Barriers

Despite emerging recognition of the necessity of climate change adaptation, many barriers still impede efforts to build local, regional, and national-level resilience. Barriers are obstacles that can delay, divert, or temporarily block the adaptation process,[106] and include difficulties in using climate change projections for decision-making; lack of resources to begin and sustain adaptation efforts; lack of coordination and collaboration within and across political and natural system boundaries as well as within organizations; institutional constraints; lack of leadership; and divergent risk perceptions/cultures and values (Table 28.6).[11,20,107] Barriers are distinguished from physical or ecological limits to adaptation, such as physiological tolerance of species to changing climatic conditions that cannot be overcome (except with technology or some other physical intervention).[8,54,108]

Despite barriers, individuals within and across sectors and regions are organizing to collectively overcome barriers and adapt to climate change. In many cases, lessons learned from initial programs help inform future adaptation strategies. Figure 28.4 highlights ongoing climate adaptation activities that have overcome some of these barriers in different regions led

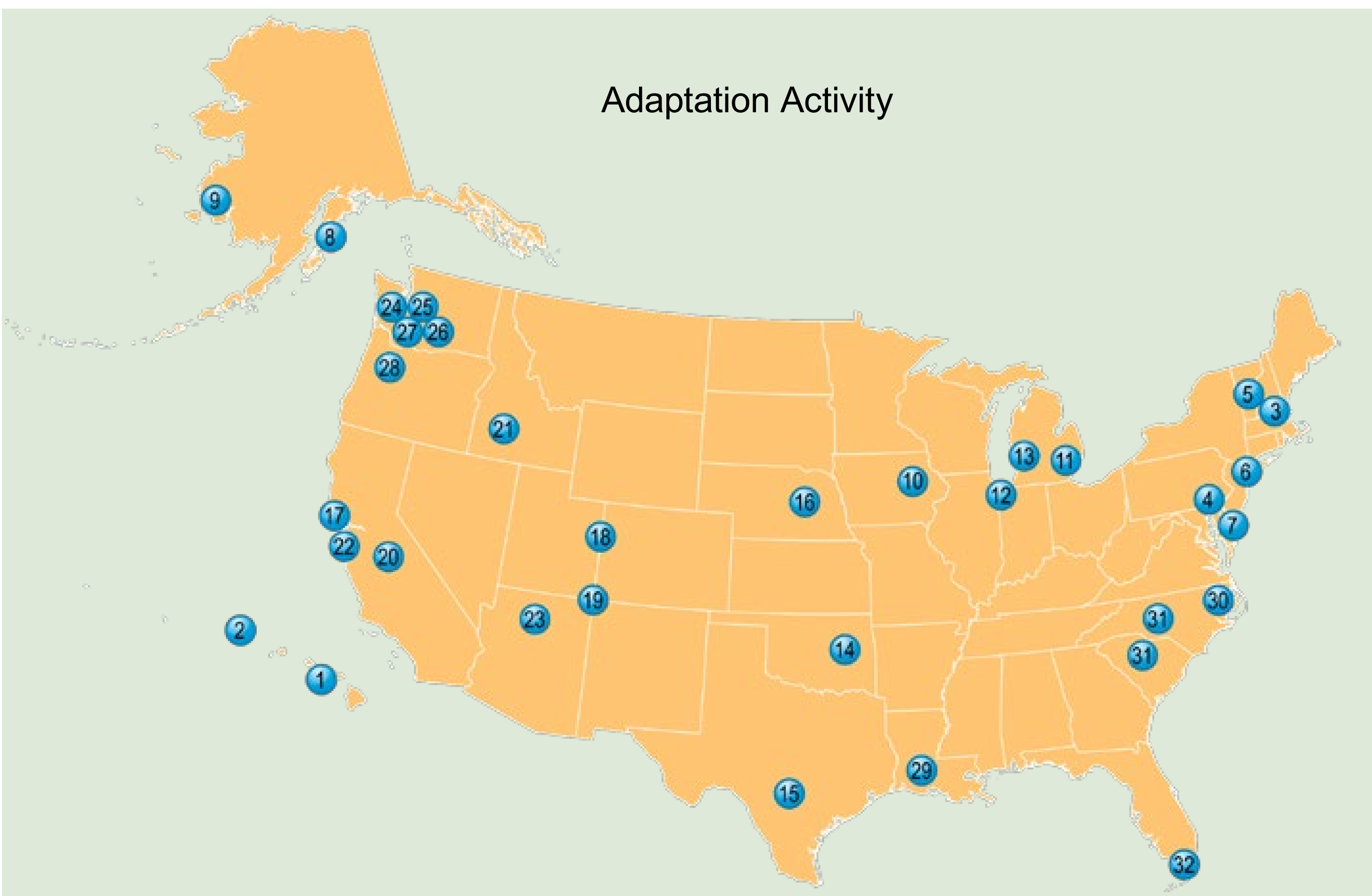
Table 28.6. Summary of Adaptation Barriers

Barrier	Specific Examples
Climate Change Information and Decision-Making References: 7,8,10,11,14,17,31,32,42,59,68,69,72,82,90,93,104,109,110,111,112	• Uncertainty about future climate impacts and difficulty in interpreting the cause of individual weather events • Disconnect between information providers and information users • Fragmented, complex, and often confusing information • Lack of climate education for professionals and the public • Lack of usability and accessibility of existing information • Mismatch of decision-making timescales and future climate projections
Lack of Resources to Begin and Sustain Adaptation Efforts References:[8,13,42,51,54,59,81,82,111,112,113,114]	• Lack of financial resources / no dedicated funding • Limited staffing capacity • Underinvestment in human dimensions research
Fragmentation of Decision-Making References:[8,14,31,32,51,68,115,116]	• Lack of coordination within and across agencies, private companies, and non-governmental organizations • Uncoordinated and fragmented research efforts • Disjointed climate related information • Fragmented ecosystem and jurisdictional boundaries
Institutional Constraints References:[8,13,42,51,54,97,113,117,118,119]	• Lack of institutional flexibility • Rigid laws and regulations • No legal mandate to act • Use of historical data to inform future decisions • Restrictive management procedures • Lack of operational control or influence
Lack of Leadership References:[30,96,112,113,119,120,121]	• Lack of political leadership • Rigid and entrenched political structures • Polarization
Divergent Risk Perceptions, Cultures, and Values References:[51,71,82,116,117,120,122]	• Conflicting values/risk perceptions • Little integration of local knowledge, context, and needs with traditional scientific information • Cultural taboos and conflict with cultural beliefs • Resistance to change due to issues such as risk perception

by state, local, and private actors in the United States. It is not a comprehensive compilation of national adaptation activity, but is intended to identify some of the variety of adaptation efforts taking place across the country.

In addition, Section 4 of this chapter provides four in-depth case studies of climate adaptation strategies at different scales, with multiple stakeholders, and tackling different challenges. Each of these case studies highlights the different ways stakeholders are approaching adaptation.

- Through the creation of the National Integrated Drought Information System (NIDIS), the Federal Government, in partnership with the National Drought Mitigation Center (NDMC), states, tribes, universities, and others, has improved capacity to proactively manage and respond to drought-related risks and impacts through: 1) the provision of drought early warning information systems with local/regional input on extent, onset, and severity; 2) a web-based drought portal featuring the U.S. Drought Monitor and other visualization tools; 3) coordination of research in support and use of these systems; and 4) leveraging of existing partnerships, forecasting, and assessment programs.
- In the Colorado River Basin, water resource managers, government leaders, federal agencies, tribes, universities, nongovernmental organizations (NGOs), and the private sector are collaborating on strategies for managing water under a changing climate through partnerships like the Western Governors' Association (WGA) and WestFAST (Western Federal Agency Support Team).
- In Wisconsin, the Northern Institute of Applied Climate Science and the U.S. Forest Service, working with multiple partners, initiated a "Climate Change Response Framework" integrating climate-impacts science with forest management.
- In Cape Cod, Massachusetts, the U.S. Department of Transportation's Volpe Center worked with federal, regional, state, and local stakeholders to integrate climate change mitigation and adaptation considerations into existing and future transportation, land-use, coastal, and hazard-mitigation processes.



Continued

Figure 28.4. Adaptation Activity

1. The State of Hawai‘i, Office of Planning, in cooperation with university, private, state, and federal scientists and others, has drafted a framework for climate change adaptation that identifies sectors affected by climate change, and outlines a process for coordinated statewide adaptation planning.[123]

2. One of the priorities of the Hawai‘i State Plan is preserving water sources through forest conservation, as indicated in their "Rain Follows The Forest" report.[124]

3. New England Federal Partners is a multi-agency group formed to support the needs of the states, tribes, and communities of the New England Region and to facilitate and enable informed decision-making on issues pertaining to coastal and marine spatial planning, climate mitigation, and climate adaptation throughout the region.[125]

4. Philadelphia is greening its combined sewer infrastructure to protect rivers, reduce greenhouse gas emissions, improve air quality, and enhance adaptation to a changing climate.[126]

5. Keene, NH, developed a Comprehensive Master Plan that emphasizes fostering walkable, mixed-use neighborhoods by putting services, jobs, homes, arts and culture, and other community amenities within walking distance of each other. The plan also calls for sustainable site and building designs that use resources efficiently. These strategies were identified in the city's 2007 Adaptation Plan as ways to build resilience while reducing greenhouse gas emissions.[127]

6. New York City has created a Green Infrastructure Plan and is committed to goals that include the construction of enough green infrastructure throughout the city to manage 10% of the runoff from impervious surfaces by 2030.[128]

7. Lewes, DE, undertook an intensive stakeholder process to integrate climate change into the city's updated hazard mitigation plan.[62]

8. Local governments and tribes throughout Alaska, such as those in Homer, are planting native vegetation and changing the coastal surface, moving inland or away from rivers, and building riprap walls, seawalls or groins, which are shore-protection structures built perpendicular to the shoreline (see also: Ch. 22:Alaska; Ch. 12: Indigenous Peoples).[129]

9. Alaskan villages are physically being relocated because of climate impacts such as sea level rise and erosion; these include Newtok, Shishmaref, Kivalina, and dozens of other villages.[130]

10. Cedar Falls, Iowa, passed legislation in 2009 that includes a new floodplain ordinance that expands zoning restrictions from the 100-year floodplain to the 500-year floodplain, because this expanded floodplain zone better reflects the flood risks experienced by the city during the 2008 floods.[131]

11. In January 2011, the Michigan Department of Community Health (MDCH) released the *Michigan Climate and Health Adaptation Plan*, which has a goal of "preparing the public health system in Michigan to address the public health consequences of climate change in a coordinated manner." In September 2010, MDCH received three years' funding to implement this plan as part of the Climate-Ready States and Cities Initiative of CDC.[132]

12. Chicago was one of the first cities to officially integrate climate adaptation into a citywide climate adaptation plan. Since its release, a number of strategies have been implemented to help the city manage heat, protect forests, and enhance green design, such as their work on green roofs.[64]

13. Grand Rapids, MI, recently released a sustainability plan that integrates future climate projections to ensure that the economic, environmental, and social strategies embraced are appropriate for today as well as the future.[133]

14. Tulsa, OK, has a three-pronged approach to reducing flooding and managing stormwater: a) prevent new problems by looking ahead and avoiding future downstream problems from new development (for example, requiring on-site stormwater detention); b) correct existing problems and learn from disasters to reduce future disasters (for example, through watershed management and the acquisition and relocation of buildings in flood-prone areas); and c) act to enhance the safety, environment, and quality of life of the community through public awareness, an increase in stormwater quality, and emergency management.[134]

15. Firewise Communities USA is a nationwide program of the National Fire Protection Association and is co-sponsored by USDA Forest Service, DOI, and the National Association of State Foresters. According to the Texas Forest Service, there are more than 20 recognized Texas Firewise Communities. The Texas Forest Service works closely with communities to help them to reach Firewise Community status and offers a variety of awareness, educational, informational, and capacity-building efforts, such as *Texas Wildscapes*, a program that assists in choosing less fire-friendly plants.[135]

Continued

16. After the heavy rainfall events of 2004 that resulted in significant erosion on his farms, Dan Gillespie, a farmer with the Natural Resources Conservation Service in Norfolk, NE, began experimenting with adding cover crops to the no-till process. It worked so well in reducing erosion and increasing crop yields that he is now sharing his experience with other farmers. (http://www.lenrd.org/projects-programs/; http://www.notill.org/)[136]

17. Point Reyes National Seashore is preparing for climate change by removing two dams that are barriers to water flow and fish migration. This change restores ecological continuity for anadromous fish (those that migrate from the sea to fresh water to spawn), creating a more resilient ecosystem.[137]

18. Western Adaptation Alliance is a group of eleven cities in five states in the Intermountain West that share lessons learned in adaptation planning, develop strategic thinking that can be applied to specific community plans, and join together to generate funds to support capacity building, adaptation planning, and vulnerability assessment.[138]

19. Navajo Nation used information on likely changes in future climate to help inform their drought contingency plan.[139]

20. California Department of Health and the Natural Resources Defense Council collaborated to create the *Public Health Impacts of Climate Change in California: Community Vulnerability Assessment and Adaptation Strategies* report, which is being used to inform public health preparedness activities in the state.[140]

21. State of Idaho successfully integrated climate adaptation into the state's Wildlife Management Plan. (http://fishandgame.idaho.gov/public/wildlife/cwcs/)[8]

22. The Rising Tides Competition was held in 2009 by the San Francisco Bay Conservation and Development Commission to elicit ideas for how the Bay could respond to sea level rise.[141]

23. Flagstaff, Arizona, created a resilience strategy and passed a resilience policy, as opposed to a formal adaptation plan, as a means to institutionalize adaptation efforts in city government operations.[142]

24. The Olympic National Forest and Olympic National Park were sites of case studies looking at how to adapt management of federal lands to climate change. Sensitivity assessments, review of management activities and constraints, and adaptation workshops in the areas of hydrology and roads, fish, vegetation, and wildlife were all components of the case study process.[143]

25. King County Flood Control District was reformed to merge multiple flood management zones into a single county entity for funding and policy oversight for projects and programs – partly in anticipation of increased stormwater flows due to climate change.[144]

26. The Water Utilities Climate Alliance has been working with member water utilities to ensure that future weather and climate considerations are integrated into short- and long-term water management planning. (http://www.wucaonline.org/html/)[90]

27. Seattle's RainWatch program uses an early warning precipitation forecasting tool to help inform decisions about issues such as drainage operations. (http://www.atmos.washington.edu/SPU/)[19]

28. City of Portland and Multnomah County created a Climate Action Plan that includes indicators to help them gauge progress in planning and implementing adaptation actions.[145]

29. In 2010, the state of Louisiana launched a $10 million program to assist communities that had been affected by Hurricanes Gustav and Ike in becoming more resilient to future environmental problems. Twenty-nine communities from around the state were awarded resiliency development funds. The Coastal Sustainability Studio at Louisiana State University started working in 2012 with all 29 funded communities, as well as many that did not receive funds, to develop peer-learning networks, develop best practices, build capacity to implement plans, and develop planning tools and a user-inspired and useful website to increase community resiliency in the state.[146]

30. U.S. Fish and Wildlife Service and The Nature Conservancy are cooperating in a pilot adaptation project to address erosion and saltwater intrusion, among other issues, in the Alligator River Refuge. This project incorporates multiple agencies, native knowledge, community involvement, local economics, and technical precision.[147]

31. North and South Carolina are actively working to revise their state wildlife strategies to include climate adaptation.[82]

32. The Southeast Florida Climate Change Compact is a collaboration of the four southernmost counties in Florida (Monroe, Broward, Palm Springs, and Miami-Dade) focusing on enhancing regional resilience to climate change and reducing regional greenhouse gas emissions.[67]

Section 3: Next Steps

Adaptation to climate change is in a nascent stage. The Federal Government is beginning to develop institutions and practices necessary to cope with climate change, including efforts such as regional climate centers within the U.S. Department of Agriculture, the National Oceanic and Atmospheric Administration (a division of the U.S. Department of Commerce), and the U.S. Department of the Interior. While the Federal Government provides financial assistance in federally-declared disasters, it is also enabling and facilitating early adaptation within states, regions, local communities, and the public and private sectors.[11] The approaches include working to limit current institutional constraints to effective adaptation, funding pilot projects, providing useful and usable adaptation information – including disseminating best practices and helping develop tools and techniques to evaluate successful adaptation.

Despite emerging efforts, the pace and extent of adaptation activities are not proportional to the risks to people, property, infrastructure, and ecosystems from climate change; important opportunities available during the normal course of planning and management of resources are also being overlooked. A number of state and local governments are engaging in adaptation planning, but most have not taken action to implement the plans.[107] Some companies in the private sector and numerous non-governmental organizations have also taken early action, particularly in capitalizing on the opportunities associated with facilitating adaptive actions. Actions and collaborations have occurred across all scales. At the same time, barriers to effective implementation continue to exist (see Section 2).

One of the overarching key areas of focus for global change research is enabling research and development to advance adaptation across scales, sectors, and disciplines. This includes social science research for overcoming the barriers identified in Section 2, such as strategies that foster coordination, better communication, and knowledge sharing amongst fragmented governing structures and stakeholders. Research on the kinds of information that users desire and how to deliver that information in contextually appropriate ways and research on decision-making in light of uncertainty about climate change and other considerations will be equally important. In addition to these areas, emerging areas of emphasis include:

- Costs and Benefits of Adaptation: Methodologies to evaluate the relevant costs of adaptation options, as well as the costs of inaction, need to be developed.[6,102]

- A Compendium of Adaptation Practices: A central and streamlined database of adaptation options implemented at different scales in space and time is needed. Information on the adaptation actions, how effective they were, what they cost, and how monitoring and evaluation were conducted should be part of the aggregated information.[11,20,31]

- Adaptation and Mitigation Interactions: Research and analysis on the growing and competing demands for land, water, and energy and how mitigation actions could affect adaptation options, and vice versa.[4,27,81,148]

- Critical Adaptation Thresholds: Research to identify critical thresholds beyond which social and/or ecological systems are unable to adapt to climate change. This should include analyzing historical and geological records to develop models of "breakpoints".[2,31,149]

- Adaptation to Extreme Events: Research on preparedness and response to extreme events such as droughts, floods, intense storms, and heat waves in order to protect people, ecosystems, and infrastructure. Increased attention must be paid to how extreme events and variability may change as climate change proceeds, and how that affects adaptation actions.[11,150]

Effective adaptation will require ongoing, flexible, transparent, inclusive, and iterative decision-making processes, collaboration across scales of government and sectors, and the continual exchange of best practices and lessons learned. All stakeholders have a critical role to play in ensuring the preparedness of our society to extreme events and long-term changes in climate.

Section 4: Case Studies

Illustrative Case One: National Integrated Drought Information System

NIDIS (National Integrated Drought Information System), originally proposed by the Western Governors' Association (WGA) and established by Congress in 2006,[151] is a federally-created entity that improves the nation's capacity to proactively manage drought-related risks across sectors, regions, and jurisdictions. It was created by Congress to "enable the Nation to move from a reactive to a more proactive approach to managing drought risks and impacts." NIDIS has successfully brought together government partners and research organizations to advance a warning system for drought-sensitive areas.

The creation of NIDIS involved many years of development and coordination among federal, state, local, regional, and tribal partners with the help of Governors' associations and Senate and Congressional leaders. NIDIS provides: 1) drought early warning information systems with regional detail concerning onset and severity; 2) a web-based portal (www.drought.gov);

3) coordination of federal research in support of and use of these systems; and 4) leveraging of existing partnerships and of forecasting and assessment programs. NIDIS currently supports work on water supply and demand, wildfire risk assessment and management, and agriculture. Regional drought early warning system pilot projects have been established to illustrate the benefits of improved knowledge management, improved use of existing and new information products, and coordination and capacity development for early warning systems. These prototype systems are in the Upper Colorado Basin, the Apalachicola-Chattahoochee-Flint River Basin in the Southeast, the Four Corners region in the Southwest, and California. The NIDIS Outlook in the Upper Colorado Basin provides early warning information every week, for example, that is utilized by a variety of users from federal agencies, water resource management, and the recreation industry.

The Western Governors' Association, the U.S. Congress, and others have formally acknowledged that NIDIS provides a successful example of achieving effective federal-state partnerships by engaging both leadership and the public, and establishing an authoritative basis for integrating monitoring and research to support risk management. Some of NIDIS's keys to success include:

- Usable Technology and Information for Decision Support: The production of the U.S. Drought Monitor map, which integrates multiple indicators and indices from many data sources, was developed before NIDIS was established and has become a useful visual decision support tool for monitoring and characterizing drought onset, severity, and persistence. NIDIS has engaged regional and local experts in refining the regional details of this national product and in "ground truthing" maps via email discussions and webinars (Figure 28.5).

- Financial Assistance: Federal funding was allocated to NOAA specifically for NIDIS, but leveraged in kind by other agencies and partners.

- Institutional/Partnerships: Effective collaborations, partnerships, and coordination with NOAA, WGA, USDA, DOI, and USGS as well as local, regional, state, and tribal partners and with the National Drought Mitigation Center at the University of Nebraska, Lincoln, have led to multi-institutional "buy-in."

- Institutional/Policy: The NIDIS Act was oriented toward the improvement of coordination across federal agencies and with regional organizations, universities, and states. It focused on the application of technology, including the Internet, and on impact assessments for decision support. A key aspect of NIDIS is the development of an ongoing regional outlook forum based on the above information to build awareness of the drought hazard and to embed information in planning and practice (in partnership with the National Drought Mitigation Center, the Regional Integrated Sciences and Assessments (RISA), and other research-based boundary organizations) to reduce risks and impacts associated with drought.

- Leadership and Champions: NIDIS supporters worked at all levels over more than two decades (1990s and 2000s) to establish the NIDIS Act, including political groups (WGA, Southern Governors' Association, National Governors Association, and U.S. Senators and Representatives), scientific leaders, and federal agencies (NOAA, USDA, DOI).

- Risk Perceptions: Whereas drought had been considered primarily a western issue in previous decades, drought is now regularly affecting the southern, southeastern, and northeastern parts of the country and response strategies are needed. During the 2012 drought, more than 63% of the contiguous U.S. by the end of July was classified as experiencing moderate to exceptional drought, and more than 3,200 heat records were broken in June 2012 alone.[152]

U.S. Drought Monitor
August 14, 2012

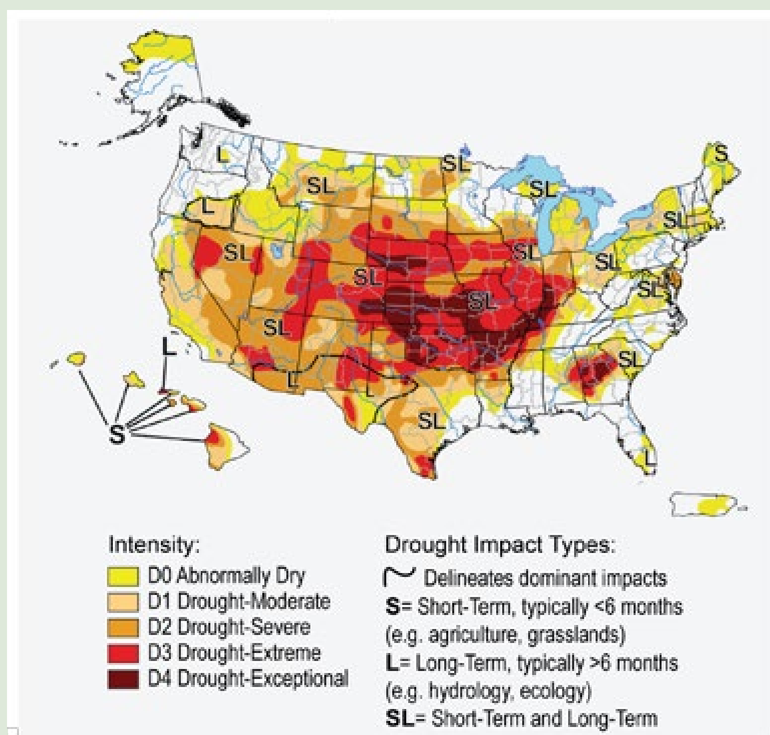


Figure 28.5. U.S. Drought Monitor Map accessed on August 20, 2012. The U.S. Drought Monitor is produced in partnership between the national Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC-UNL.

Illustrative Case Two: Adaptive Governance in the Colorado River Basin

The Colorado River supplies water and valuable ecosystem services to 33 million people and is vulnerable to climate change because of decreases in mountain snowpack and water availability, increased competition among water users, fires, drought, invasive species, and extended extreme heat events, among other threats.[13,153] The 1922 Colorado River Compact, which allocates water among seven U.S. states and Mexico, was agreed upon in a particularly wet time period;[154] thus the river water is already over-allocated for current conditions. Given the likelihood of having less water because of climate change, resource managers and government leaders are increasingly recognizing that water must be managed with flexibility to respond to the projected impacts and the range of possible future climates (see Ch. 2: Our Changing Climate; Ch. 3: Water).[13,155] Multiple actors across multiple disciplines, scales of governance (including tribal, local, state, and federal), non-governmental organizations, and the private sector are organizing and working together to address these concerns and the relationship between climate and other stresses in the basin.

The Western Governors' Association (WGA) spearheaded adaptation efforts to enable federal, state, tribal, local, and private sector partners to address a range of issues, including climate change.[13,155,156] For example, the Western Federal Agency Support Team (WestFAST), which was established in 2008, created a partnership between the Western States Water Council (WSWC) and 11 federal agencies with water management responsibilities in the western United States. The agencies created a work plan in 2011 to address three key areas: 1) climate change; 2) water availability, water use, and water reuse; and 3) water quality. To date they have produced the WestFAST Water-Climate Change Program Inventory, the Federal Agency Summary, and a Water Availability Studies Inventory (http://www.westgov.org/wswc/WestFAST.htm).

The WSWC and the USACE produced the Western States Watershed Study (WSWS), which demonstrated how federal agencies could work collaboratively with western states on planning activities.[157] In 2009, the WGA also adopted a policy resolution titled "Supporting the Integration of Climate Change Adaptation Science in the West" that created a Climate Adaptation Work Group composed of western state experts in air quality, forest management, water resources, and wildlife management. Other important adaptation actions were the SECURE Water Act in 2009, the Reclamation Colorado River Basin water supply and demand study, and the creation of NIDIS to support stakeholders in coping with drought.[151,158]

Illustrative Case Three: Climate Change Adaptation in Forests

Northern Wisconsin's climate has warmed over the past 50 years, and windstorms, wildfires, insect outbreaks, and floods are projected to become more frequent in this century.[160] The resulting impacts on forests, combined with fragmented and complex forest ownership, create management challenges that extend across ownership boundaries, creating the need for a multi-stakeholder planning process.[161]

To address these concerns, the Northern Institute of Applied Climate Science, the USDA's Forest Service, and many other partners initiated the Climate Change Response Framework to incorporate scientific research on climate change impacts into on-the-ground management. Originally developed as a pilot project for all-lands conservation in northern Wisconsin, it has expanded to cover three ecological regions (Northwoods [Figure 28.6], Central Hardwoods, and Central Appalachians) across eight states in the Midwest and Northeast. The Framework uses a collaborative and iterative approach to provide information and resources to forest owners and managers across a variety of private and public organizations. Several products were developed through the Framework in northern Wisconsin:

Figure 28.6. Northwoods Climate Change Response Framework Region (Figure Source: USDA Forest Service 2012[159]).

1. Vulnerability and mitigation assessments summarized the observed and projected changes in the northern Wisconsin climate, projected changes in forest composition and carbon stocks across a range of potential climates, and assessed related vulnerabilities of forest ecosystems in northern Wisconsin.[160]

2. Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers[162] was developed to help managers identify management tactics that facilitate adaptation. A "menu" of adaptation strategies and approaches for planning, implementing, and monitoring adaptation activities was synthesized into an adaptation workbook from a broad set of literature and refined based on feedback from regional scientists and managers.[163]

3. A series of adaptation demonstrations was initiated to showcase ground-level implementation. The Framework and adaptation workbook provide a common process shared by diverse landowners and a formal network that supports

cross-boundary discussion about different management objectives, ecosystems, and associated adaptation tactics.

From the beginning, the Framework has taken an adaptive management approach in its adaptation planning and projects. Lessons learned include:

- Define the purpose and scope of the Framework and its components early, but allow for refinement to take advantage of new opportunities.
- Begin projects with a synthesis of existing information to avoid duplicating efforts.
- Plan for the extra time necessary to implement true collaboration.
- Carefully match the skills, commitment, and capacity of people and organizations to project tasks.
- Maintain an atmosphere of trust, positivity, and sense of adventure, rather than dwelling on failures.
- Acknowledge and work with uncertainty, rather than submit to "uncertainty paralysis."
- Recognize the necessity of effective communication among people with different goals, disciplinary backgrounds, vocabulary, and perspectives on uncertainty.
- Integrate the ecological and socioeconomic dimensions early by emphasizing the many ways that communities value and depend on forests.
- Use technology to increase efficiency of internal communication and collaboration, as well as outreach.

The Framework brings scientists and land managers together to assess the vulnerability of ecosystems based on scientific information and experience in order to plan adaptation actions that meet management goals. On-the-ground implementation has just begun, and an increased focus on demonstrations, monitoring, and evaluation will inform future adaptation efforts.

Illustrative Case Four: Transportation, Land Use, and Climate Change – Integrating Climate Adaptation and Mitigation in Cape Cod, Massachusetts

Cape Cod, Massachusetts, a region of scenic beauty and environmental significance, is currently affected by sea level rise, coastal erosion, and localized flooding – impacts that are likely to be exacerbated by climate change.[164,165] To address these concerns and help meet the state's greenhouse gas (GHG) reduction target (25% reduction based on 1990 levels by 2020), the U.S. Department of Transportation's Volpe Center worked with federal, regional, state, and local stakeholders to integrate climate change into existing and future transportation, land-use, coastal zone, and hazard mitigation planning through an initiative called the Transportation, Land Use, and Climate Change Pilot Project.[164,166]

The process was initiated through an expert elicitation held in mid-2010 to identify areas on Cape Cod that are or could potentially be vulnerable to sea level rise, flooding, and erosion. The Volpe Center then used a geographic information system (GIS) software tool to develop and evaluate a series of transportation and land-use scenarios for the Cape under future development projections.[165,167] All scenarios were evaluated against a series of criteria that included: 1) reduction in vehicle miles traveled; 2) reduced heat-trapping gas emissions; 3) reduction in transportation energy use; 4) preservation of natural/existing ecosystems; 5) reduction in percentage of new population in areas identified as vulnerable to climate change impacts; and 6) increased regional accessibility to transportation.[164]

Once the preliminary scenarios were developed, a workshop was convened in which community and transportation planners, environmental managers, and Cape Cod National Seashore stakeholders selected areas for development and transit improvements to accommodate new growth while meeting the goals of reduced heat-trapping gas emissions, increased resilience to climate change, and the conservation of natural systems.[165] Through interactive visualization tools, participants were able to see in real-time the impacts of their siting decisions, allowing them to evaluate synergies and potential tradeoffs of their choices and to highlight areas where conflict could or already does exist, such as increasing density of development in areas already or likely to be vulnerable to climate change.[168] As a result, the stakeholders developed a refined transportation and land-use scenario that will support the region's long-range transportation planning as well as other local, regional, and state plans. This updated scenario identifies strategies that have climate adaptation and mitigation value, helping to ensure that the region simultaneously reduces its heat-trapping gas footprint while building resilience to existing and future changes in climate.[164,165] The overall success of the pilot project stemmed from the intensive stakeholder interaction at each phase of the project (design, implementation, and evaluation).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages
A central component of the process were bi-weekly technical discussions held from October 2011 to June 2012 via teleconference that focused on collaborative review and summary of all technical inputs relevant to adaptation (130+) as well as additional published literature, the iterative development of key messages, and the final drafting of the chapter. An in-person meeting was held in Washington, D.C., in June 2012. Meeting discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each key message. Consensus was reached on all key messages and supporting text.

Key message #1 Traceable Account

Substantial adaptation planning is occurring in the public and private sectors and at all levels of government; however, few measures have been implemented and those that have appear to be incremental changes.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications indicate that a growing number of sectors, governments at all scales, and private and non-governmental actors are starting to undertake adaptation activity.[9,13] Much of this activity is focused on planning with little literature documenting implementation of activities.[8,11,82] Supporting this statement is also plentiful literature that profiles barriers or constraints that are impeding the advancement of adaptation activity across sectors, scales, and regions.[42,68]

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties
n/a

Assessment of confidence based on evidence
n/a

Key message #2 Traceable Account

Barriers to implementation of adaptation include limited funding, policy and legal impediments, and difficulty in anticipating climate-related changes at local scales.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the peer reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input. A significant quantity of reviewed literature profiles barriers or constraints that are impeding the advancement of adaptation activity across sectors, scales, and regions.[11,20,42,68]

Numerous peer-reviewed documents describe adaptation barriers (see Table 28.6). Moreover, additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties
n/a

Assessment of confidence based on evidence
n/a

Key message #3 Traceable Account

There is no "one-size fits all" adaptation, but there are similarities in approaches across regions and sectors. Sharing best practices, learning by doing, and iterative and collaborative processes including stakeholder involvement, can help support progress.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Literature submitted for this assessment, as well as additional literature reviewed by the author team, fully supports the concept that adaptations will ultimately need to be selected for their local applicability based on impacts, timing, political structure, finances, and other criteria.[11,90] Similarities do exist in the types of adaptation being implemented, although nuanced differences do make most adaptation uniquely appropriate for the specific implementer. The selection of locally and context-appropriate adaptations is enhanced by iterative and collaborative processes in which stakeholders directly engage with decision-makers and information providers.[11,20,28] While there are no "one-size fits all" adaptation strategies, evidence to date supports the message that the sharing of best practices and lessons learned are greatly aiding in adaptation progress across sectors, systems, and governance systems.[82,86]

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

Key message #4 Traceable Account

Climate change adaptation actions often fulfill other societal goals, such as sustainable development, disaster risk reduction, or improvements in quality of life, and can therefore be incorporated into existing decision-making processes.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Literature submitted for this assessment, as well as additional literature reviewed by the author team, supports the message that a significant amount of activity that has climate adaptation value is initiated for reasons other than climate preparedness and/or has other co-benefits in addition to increasing preparedness to climate and weather impacts.[11,20,82,86,116] In recognition of this and other factors, a movement has emerged encouraging the integration of climate change considerations into existing decision-making and planning processes (i.e., mainstreaming).[5,11,40] The case studies discussed in the chapter amplify this point.

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

Key message #5 Traceable Account

Vulnerability to climate change is exacerbated by other stresses such as pollution, habitat fragmentation, and poverty. Adaptation to multiple stresses requires assessment of the composite threats as well as tradeoffs amongst costs, benefits, and risks of available options.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Climate change is only one of a multitude of stresses affecting social, environmental, and economic systems. Activity to date and literature profiling those activities support the need for climate adaptation activity to integrate the concerns of multiple stresses in decision-making and planning.[16,17,32] As evidenced by activities to date, integrating multiple stresses into climate adaptation decision-making and vice versa will require the assessment of tradeoffs amongst costs, benefits, the risks of available options, and the potential value of outcomes.[5,90,111]

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties

n/a

Assessment of confidence based on evidence

n/a

Key message #6 Traceable Account

The effectiveness of climate change adaptation has seldom been evaluated, because actions have only recently been initiated and comprehensive evaluation metrics do not yet exist.

Description of evidence base

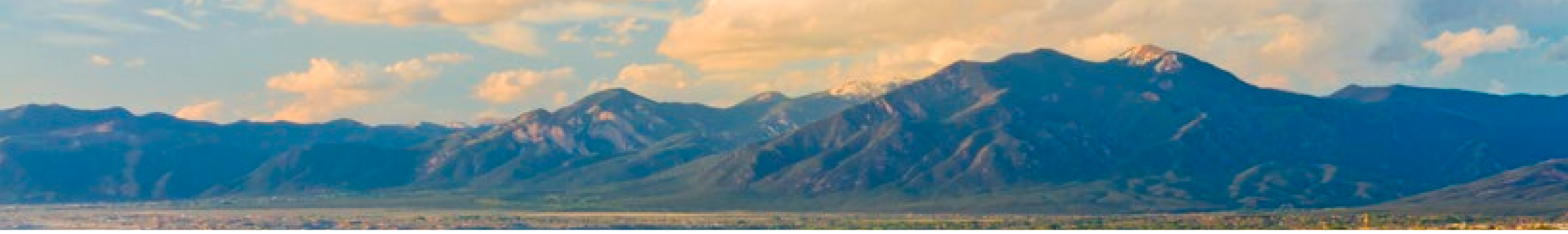
The key message and supporting text summarize extensive evidence documented in the peer-reviewed literature as well as the more than 130 technical inputs received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications indicate that no comprehensive adaptation evaluation metrics exist, meaning that no substantial body of literature or guidance materials exist on how to thoroughly evaluate the success of adaptation activities.[11,81,110] This is an emerging area of research. A challenge of creating adaptation evaluation metrics is the growing interest in mainstreaming; this means that separating out adaptation activities from other activities could prove difficult.

Additional citations are used in the text of the chapter to substantiate this key message.

New information and remaining uncertainties
n/a

Assessment of confidence based on evidence
n/a



Climate Change Impacts in the United States

CHAPTER 29
RESEARCH NEEDS FOR CLIMATE AND GLOBAL CHANGE ASSESSMENTS

Convening Lead Authors

Robert W. Corell, Florida International University and the GETF Center for Energy and Climate Solutions

Diana Liverman, University of Arizona

Lead Authors

Kirstin Dow, University of South Carolina

Kristie L. Ebi, ClimAdapt, LLC

Kenneth Kunkel, CICS-NC, North Carolina State Univ., NOAA National Climatic Data Center

Linda O. Mearns, National Center for Atmospheric Research

Jerry Melillo, Marine Biological Laboratory

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On the Web: http://nca2014.globalchange.gov/report/response-strategies/research-needs

29 RESEARCH NEEDS FOR CLIMATE AND GLOBAL CHANGE ASSESSMENTS

Overview

This chapter identifies key areas of research to provide foundational understanding and advance climate assessments. Many of these research topics overlap with those needed for advancing scientific understanding of climate and its impacts and for informing a broader range of relevant decisions.

The research areas and activities discussed in this chapter were identified during the development of the regional and sectoral technical input reports, from the contributions of over 250 National Climate Assessment (NCA) chapter authors and experts, and from input from reviewers. The five high-level research goals, five foundational cross-cutting research capabilities, and more specific research elements described in this chapter also draw from a variety of previous reports and assessments. These lists are provided as recommendations to the Federal Government. Priority activities for global change research across 13 federal agencies are coordinated by the U.S. Global Change Research Program, which weighs all activities within the more than $2 billion annual climate science portfolio relative to one another, considering agency missions, priorities, and budgets.

The last National Climate Assessment report, released by the U.S. Global Change Research Program (USGCRP) in 2009, recommended research on: 1) climate change impacts on ecosystems, the economy, health, and the built environment; 2) projections of climate change and extreme events at local scales; 3) decision-relevant information on climate change and its impacts; 4) thresholds that could lead to abrupt changes in climate or ecosystems; 5) understanding the ways to reduce the rate and magnitude of climate change through mitigation; and 6) understanding how society can adapt to climate change.[1]

Some of these topics have received continued or increased attention in the last five years – such as ecosystem impacts, downscaled climate projections, and mitigation options – but the current assessment finds that significant knowledge gaps remain for all of the research priorities identified in 2009. This conclusion is reinforced by the findings of many subsequent reviews by the National Research Council (NRC) and others who have continued to identify these as priorities. For example, the NRC's *America's Climate Choices Panel on Advancing the Science of Climate Change and the Panel on Informing Effective Decisions and Actions*[2,3] highlighted several priorities that are relevant to climate assessments (see "Cross-Cutting Themes for the New Era of Climate Change Research Identified by America's Climate Choices"). These included the need for a more comprehensive, interdisciplinary, use-inspired, and integrated research enterprise that combines fundamental understanding of climate change and response choices, that improves understanding of human-environment systems; that supports effective adaptation and mitigation responses, and that provides better observing systems and projections. In recognition of fiscal limitations, it is clear that research agencies and partners will need to work together to leverage resources and ensure coordinated and collaborative approaches.

Research goals and cross-cutting capabilities

Five Research Goals

- Improve understanding of the climate system and its drivers
- Improve understanding of climate impacts and vulnerability
- Increase understanding of adaptation pathways
- Identify the mitigation options that reduce the risk of longer-term climate change
- Improve decision support and integrated assessment

Five Foundational Cross-Cutting Research Capabilities

- Integrate natural and social science, engineering, and other disciplinary approaches
- Ensure availability of observations, monitoring, and infrastructure for critical data collection and analysis
- Build capacity for climate assessment through training, education, and workforce development
- Enhance the development and use of scenarios
- Promote international research and collaboration

Cross-cutting themes for the new era of climate change research identified by *America's Climate Choices*

Research to Improve Understanding of Human-Environment Systems

1. Climate forcings, feedbacks, responses, and thresholds in the Earth system
2. Climate-related human behaviors and institutions

Research to Support Effective Responses to Climate Change

3. Vulnerability and adaptation analyses of coupled human-environment systems
4. Research to support strategies for limiting climate change
5. Effective information and decision support systems

Research Tools and Approaches to Improve Both Understanding and Responses

6. Integrated climate observing systems
7. Improved projections, analyses, and assessments

Source: *America's Climate Choices, Advancing the Science of Climate Change, National Academy of Sciences 2010*, p. 92.[4]

The U.S. Global Change Research Program's 2012-2021 Strategic Plan[5] lists a number of strategic goals and objectives for advancing science, informing decisions, conducting sustained assessments, and communicating and educating about global change. The plan includes research priorities to understand Earth system components, their interactions, vulnerability and resilience; advance observations, modeling, and information management; and evaluate assessment processes and products.

This chapter focuses specifically on the research identified through the National Climate Assessment process as needed to improve climate assessments. It is not intended to cover the full range of goals and related research priorities of the USGCRP and other groups, but instead to focus on research that will improve ongoing assessments. Therefore, many USGCRP priorities for climate change and global change science more broadly are not reflected here. The chapter does, however, directly support the USGCRP Strategic Plan's sustained assessment activities (see "Goal 3 of the USGCRP Strategic Plan").

This chapter is not intended to prescribe a specific research agenda but summarizes the research needs and gaps that emerged during development of this Third National Climate Assessment report that are relevant to the development of future USGCRP research plans.

During the development of this report, the authors were concerned that several important topics could not be comprehensively covered. In addition, several commenters noted the absence of these topics and felt that they were critical to consider in future reports. These include analyses of the economic costs of climate change impacts (and the associated benefits of mitigation and adaptation strategies); the implications of climate change for U.S. national security as a topic integrated with other regional and sectoral discussions; and the interactions of adaptation and mitigation options, including consideration of the co-benefits and potential unintended consequences of particular decisions.

Goal 3 of the USGCRP strategic plan

Conduct Sustained Assessments: Build sustained assessment capacity that improves the Nation's ability to understand, anticipate, and respond to global change impacts and vulnerabilities.

The USGCRP will conduct and participate in national and international assessments to evaluate past, current, and likely future scenarios of global change and their impacts, as well as how effectively science is being used to support and inform the United States' response to change. The USGCRP will integrate emerging scientific understanding of the Earth system into assessments and identify critical gaps and limitations in scientific understanding. It will also build a standing capacity to conduct national assessments and support those at regional levels. The USGCRP will evaluate progress in responding to change and identify science and stakeholder needs for further progress. The program will use this regular assessment to inform its priorities.

Research Goals

Research Goal 1: Improve understanding of the climate system and its drivers

Research investments across a broad range of disciplines are critically important to building understanding of, and in some cases reducing uncertainties related to, the physical and human-induced processes that govern the evolution of the climate system. This assessment demonstrates the continued need for high quality data and observations, analysis of Earth system processes and changes, and modeling that increases understanding and projections of climate change across scales. Social science research is also essential to improved understanding and modeling of the drivers of climate change, such as energy use and land-use change, as well as understanding impacts (see Research Goal 2). Assessing a changing climate requires understanding the role of feedbacks, thresholds, extreme events, and abrupt changes and exploring a range of scenarios (see Cross-Cutting Research Capabilities section) that drive changes in the climate system.

This assessment reveals several research needs including:

- **Continue efforts to improve the understanding, modeling, and projections of climate changes,** especially at the regional scale, including driving forces of emissions and land-use change, changes in temperature, precipitation, soil moisture, runoff, groundwater, evapotranspiration, permafrost, ice and snow cover, sea level change, and ocean processes and chemistry;

- **Improve characterization of important sources of uncertainty, including feedbacks and possible thresholds in the climate system** associated with changes in clouds, land and sea ice, aerosols (tiny particles in the atmosphere), greenhouse gases, land use and land cover, emissions scenarios, and ocean dynamics;

- **Develop indicators that allow for timely reporting and enhanced public understanding** of climate changes and that allow anticipation and attribution of changes, including abrupt changes and extreme events in the context of a changing climate; and

- **Advance understanding of the interactions of climate change and natural variability** at multiple time scales, including seasonal to decadal changes (and consideration of climate oscillations including the El Niño Southern Oscillation, Pacific Decadal Oscillation, and the North Atlantic Oscillation), and extreme events (such as hurricanes, droughts, and floods).

Research Goal 2: Improve understanding of climate impacts and vulnerability

Assessing the implications of climate change for the U.S. relies not just on studies of the threats associated with changing weather patterns due to climate change and emerging chronic stresses such as sea level rise, but also on studies of who or what is exposed and sensitive to those threats, their underlying vulnerability, the associated costs, and adaptive capacity. The detailed sectoral and regional chapters of this assessment show that considerable progress has been made in understanding the extent to which natural and human systems in the U.S. are vulnerable to climate change and how these vulnerabilities combine with climatic trends and exposures to create impacts, but there is still a need to build capacity for assessing vulnerability.

This assessment suggests related research goals and activities including:

- **Maintain and enhance research and development of data collection and analyses to monitor and attribute ongoing and emerging climate impacts across the United States,** including changes in ecosystems, pests and pathogens, disaster losses, water resources, oceans, and social, urban, and economic systems. Priorities include ensuring enhanced geographic coverage of impacts research; the assessment of economic costs and benefits, as well as comparative studies of alternative response options; social science research focused on impacts; and the use of geospatial data systems;

- **Assess the impacts of climatic extremes, high-end temperature scenarios, and abrupt climate change** on ecosystems, health, food, water, energy, infrastructure, and other critical sectors, and improve modeling capabilities to better project and understand the vulnerability and resilience of human systems and ecosystems to climate change and other stresses such as land-use change and pollution;

- **Increase the understanding of how climate uncertainties combine with socioeconomic and ecological uncertainties** and identify improved ways to communicate the combined outcomes;

- **Develop measurement tools and valuation methods** for documenting the economic consequences of climate changes;

- **Expand climate impact analyses to focus on understudied but significant economic sectors** such as natural resources and energy development (for example, mining, oil, gas, and timber); manufacturing; infrastructure, land development, and urban areas; finance and other services; retail; and human health and well-being; and

- **Investigate how climate impacts are affected by, or increase inequity in, patterns of vulnerability of particular population groups** within the U.S. and abroad (for example, children, the elderly, the poor, and natural resource dependent communities).

Research Goal 3: Increase understanding of adaptation pathways

This assessment and others, including the *America's Climate Choices Adapting to the Impacts of Climate Change* report[2] and Chapter 4 (on adaptation and mitigation options and responses) of the Intergovernmental Panel on Climate Change's (IPCC) AR4 Synthesis Report,[6] identifies a broad set of research needs for understanding and implementing adaptation. These include research on adaptation processes, adaptive capacity, adaptation option identification, implementation and evaluation, and adaptive management of risks and opportunities.

Important needs include research on the limits to, timing of, and tradeoffs in adaptation, and understanding of how adaptation interacts with mitigation activities, other stresses, and broader sustainability issues.

This assessment suggests research activities to:

- **Identify the best practices for adaptation planning, implementation, and evaluation** across federal, state, and local agencies, tribal entities, private firms, non-governmental organizations, and local communities. This requires the rigorous and comparative analysis of the effectiveness of iterative risk management, adaptation strategies and decision support tools (for example, in terms of stakeholder views, institutional structures including regional centers and multi-agency programs, cost/benefit, assessment against stated goals or social and ecological indicators, model validation, and use of relevant information, including traditional knowledge); and

- **Understand the institutional and behavioral barriers to adaptation and how to overcome them,** including revisions to legal codes, building and infrastructure standards, urban planning, and policy practices.

Research Goal 4: Identify the mitigation options that reduce the risk of longer-term climate change

The severity of climate change impacts in the U.S. and the need for adapting to them over the longer term will depend on the success of efforts to reduce or sequester heat-trapping greenhouse gas (GHG) emissions, particularly those associated with the burning of fossil fuels but also those associated with changes in land use. Managing the consequences of climate change over this century depends on reducing concentrations of greenhouse gases, including short-lived climate pollutants such as black carbon (soot).

While such efforts are necessarily worldwide, the U.S. produces a significant share of global greenhouse gases and can assist and influence other countries to reduce their emissions. Assessments can play a significant role in providing a better information base from which to analyze mitigation options.

Therefore, the mitigation section of this assessment (Ch. 27: Mitigation) noted the importance of research to understand and develop emission reductions through: 1) identifying climate and global change scenarios and their impacts; 2) providing a range of options for reducing the risks to climate and global change; and 3) developing options that allow joint mitigation-adaptation strategies, such as buildings that are more energy efficient and resilient to climate change impacts.

More generally, the *America's Climate Choices* report on *Limiting the Magnitude of Climate Change*[3] recommended that the U.S. promptly develop and implement appropriate strategies to reduce GHG emissions and identified important research needs, including the need to study the feasibility, costs, and consequences of different mitigation options. In addition, the report recommended research to support new technologies and the effective deployment of existing options, research into how best to monitor emissions and adherence to international policies, and research into how human behavior and institutions enable mitigation.[3]

This Third National Climate Assessment also suggests research activities to:

- **Develop information that supports analysis of new technologies** for energy production and use, carbon capture and storage, agricultural and land-use practices, and other technologies that could reduce or offset greenhouse gas emissions; research into the policy mechanisms that could be used to foster their development and implementation; analyses of the costs, benefits, tradeoffs, and synergies associated with different actions and combinations of actions; and improved understanding of the potential and risks of geoengineering;

- **Investigate the co-benefits, interactions, feedbacks, and tradeoffs between adaptation and mitigation** at the local and regional level, for example, in sectors such as agriculture, forestry, energy, health, and the built environment. This involves, as a priority, the assessment of the economics of impacts, mitigation, and adaptation;

- **Improve understanding of the effectiveness and timescales of mitigation measures** through deepened understanding of the relationship between the fate of human-induced and natural carbon emissions, uptake by the terrestrial biosphere and oceans, and atmospheric concentrations; and

- **Identify the critical social, cultural, institutional, economic, and behavioral processes that present barriers and opportunities for mitigation** at the federal and international levels and by individuals, state and local governments, and corporations.

Research Goal 5: Improve decision support and integrated assessment

For assessments to be useful to policy makers, they need to provide integrated results that can be used in decision-making. Research can develop tools that facilitate decision-making and the integration of knowledge.

Critical gaps in knowledge for decision support include the issues that affect the capacity of agencies, individuals, and communities to access and use the best available scientific information in support of decision-making, including the need to assess the ability of existing institutions, legal, and regulatory structures to respond to highly interdependent climate impacts. There are instances where policy barriers, institutional capacity or structure, or conflicting laws and regulations can create barriers to effective decisions. For instance, Chapter 12 (Indigenous Peoples) notes that there is no institutional framework for addressing village relocation in response to climate change in Alaska,[7] and Chapter 3 (Water) points out that existing water management institutions may be inadequate in the context of rapidly changing conditions. These instances point to research to evaluate whether the existing legal and regulatory structures, largely developed to address specific issues in isolation, can adequately respond to the highly interconnected issues associated with climate change. Decision support and integrated assessment also require research into the behavioral and other factors that influence individual decisions.

Assessments can benefit from research activities that:

- **Identify decision-maker needs** within regions and sectors, and support the development of research methods, tools, and information systems and models for managing carbon, establishing early warning systems, providing climate and drought information services, and analyzing the legal, regulatory, and policy approaches that support adaptation and mitigation efforts in the context of a changing climate;

- **Develop tools to support risk-based decision processes**, including tools to identify risk management information needs, develop transferable vulnerability assessment techniques, and evaluate alternative adaptation options. In addition, tools are needed to improve understanding of consumption patterns and environmental consequences; effective resource management institutions; iterative risk management strategies; and social learning, cognition, and adaptive processes;

- **Improve, fill gaps, and enhance research efforts to evaluate the effectiveness, costs, and benefits of mitigation and adaptation actions,** including economic and non-economic metrics that evaluate the costs of action, inaction, and residual impacts. Focus is also needed on the development of methods and baseline information supporting evaluation of completed and ongoing adaptation, mitigation, and assessment efforts that will foster adaptive learning; and

- **Develop, test and, expand integrated assessment models** that link decisions about emissions with impacts under different development pathways and ways to categorize uncertainties in the supporting data.

Foundational Cross-Cutting Research Capabilities to Support Future Climate Assessments

This assessment identifies a set of five foundational cross-cutting research capabilities that are essential for advancing our ability to continue to conduct climate and global change assessments and for addressing the five research goals.

1. Integrate natural and social sciences, engineering, and other disciplinary approaches

Continued advances in comprehensive and useful climate assessments will rely on additional interdisciplinary research. Understanding of the coupled human-environment system is enriched by combining research from natural and social sciences with research and experience from the engineering, law, and business professions.

Because human activities and decisions are influencing many Earth system processes, models and observations of natural and social changes at planetary, regional, and local scales are needed to understand how climate is changing, its impacts on people and environments, and how human responses feedback on the Earth system.

Building experienced interdisciplinary research teams that are able to understand each other's theories, methods, and language as well as the needs of stakeholders will allow for more rapid and effective assessments.

Interdisciplinary research is needed, for example, to:

- Understand how hydrological drivers of water supply interact with changing patterns of water demand and evolving water management practices to increase risks of drought, or influence the effectiveness of adaptation and mitigation options;
- Understand climate change in the context of multiple stresses on Earth, ecological, and human systems;
- Bring together economic and quantitative assessment of climate impacts and policies with other more qualitative assessments that include non-market and cultural values; and
- Integrate the understanding of human behavior, engineering, and genomics to expand the range of choice in responding to climate change by providing and thoroughly evaluating new options for adaption and mitigation that improve economic development, energy, health, and food security.

2. Ensure availability of observations, monitoring, and infrastructure for critical data collection and analysis

Our understanding and ability to assess changes in climate and other global processes is based on a comprehensive and sustained system of observations that document the history of climate, socioeconomic, and related changes at spatial and time scales relevant to global, regional, and sectoral needs. The most recent USGCRP Strategic Plan[5] states that to advance scientific knowledge of an integrated natural and human Earth system, an interoperable and integrated observational, monitoring, and data access capability is also essential. This observational capability is needed to gain the fundamental scientific understanding of essential status, trends, variability, and changes in the Earth system. It should include the physical, chemical, biological, and human components of the Earth system over multiple space and time scales.

To attain their full value, observational systems must provide data that are responsive to the needs of decision-makers in government, industry, and society. These needs include observations and data that can inform the nation's strategies to respond to climate and global change, including, for example, efforts to limit emissions, monitor public health, capture and store carbon, monitor changes in ocean processes, and implement adaptation strategies. This will require establishing explicit baseline conditions, specifying spatial detail and temporal frequency of observations, including social data, and setting standards for metadata (information about collected data), interoperability, and regulatory and voluntary reporting, such as those outlined in the *Informing an Effective Response to Climate Change Panel Report* of the National Research Council's *Americas Climate Choices* series.[8] These data need to be openly and widely available in order to support the best and most comprehensive science and for use in decision-making by a range of stakeholders.

This assessment shows that enhanced research and development will be necessary to ensure that the scope and integration of relevant scientific data improves overall utility for decision-makers, including better ways to communicate metadata, data quality, and uncertainties. The observations must include critical geophysical variables such as temperature, precipitation, sea level changes, ocean circulation, atmospheric composition, and hydrology; the essential parameters that describe the biosphere; and social science information on drivers, impacts, and responses to climate and other global changes. More comprehensive and integrated data capabilities are needed to document the processes and patterns that drive natural and social feedbacks and better describe the mechanisms of abrupt change. Progress is needed in particular for data-poor regions, focusing on inadequately documented socioeconomic, ecological, and health-related factors, and under-observed regional and sectoral data. There are opportunities to take advantage of citizen science observations where appropriate; monitor system resilience and robustness; and attend to physical and social systems that are not currently observed with sufficient temporal or spatial resolution to enable vulnerability analysis and decision support at regional and sectoral scales. More explicitly, strategic integration of our nation's observations, monitoring, and data capabilities should be considered in order to:

- **Sustain and integrate the nation's capacity to observe** long-term changes in the Earth system and improve fundamental understanding of the complex causes and consequences of global change, including integration of essential socioeconomic, health, and ecological observations;

- **Maintain and enhance advanced modeling capability**, including high-performance computing infrastructure, improvements in analysis of large and complex data sets, comprehensive Earth system and integrated assessment models, reanalysis, verification, and model comparisons;

- **Better integrate observations and modeling** to advance scientific understanding about past, present, and future climate within government, industry, and civil society; and

- **Develop more fully the components and structure of a national climate and global change indicator system** to support assessment that includes indicators of climate change, impacts, vulnerabilities, opportunities, and preparedness as well as trends and changes in land use, air and water pollution, water supply and demand, extreme events, diseases, public health, and agronomic data, coastal and ocean conditions (such as marine ecosystem health, ocean acidity, sea level, and salinity), cryosphere data (such as snow, sea ice conditions, ice sheets and glacier melt rates), and changes in public attitudes and understanding of climate change. All of these are important to assessing climate change, and should eventually be better coordinated at local, as well as national and regional levels in collaboration with local agencies.

3. Build capacity for climate assessment through training, education, and workforce development

Building human capacity for improved assessments requires expansion of skills within the existing public and private sectors and developing a much larger workforce that excels at critical and interdisciplinary thinking. Useful capacities include the ability to facilitate and communicate research and practice, manage collaborative processes to allow for imaginative analysis and solutions, develop sustainable technologies to reduce climate risks, and build tools for decision-making in an internationally interdependent world.

A deeper understanding of the processes and impacts of climate change, disaster risk reduction, energy policy impacts, ecosystem services and biodiversity, poverty reduction, food security, and sustainable consumption requires new approaches to training and curriculum, as well as research to evaluate the effectiveness of different approaches to research and teaching.

Assessments will benefit from activities that:

- **Strengthen approaches to education about climate, impacts, and responses** including developing and evaluating the best ways to educate in the fields of science (natural and social), technology, engineering, and mathematics and related fields of study (such as business, law, medicine, and other relevant professional disciplines). Ideally, such training would include a deeper understanding of the climate system, natural resources, adaptation and energy policy options, and economic sustainability, and would build capacity at colleges and institutions, including minority institutions such as tribal colleges; and

- **Identify increasingly effective approaches to developing a more climate-informed society** that understands and can participate in assessments, including alternative media and methods for communication; this could also include a program to certify climate interpreters to actively assist decision-makers and policymakers to understand and use climate scenarios.[8]

4. Enhance the development and use of scenarios

Scenarios are "coherent, internally consistent and plausible descriptions of possible future states of the world"[9] that provide reasoned projections of energy and land use, future population levels, economic activity, the structure of governance, social values, and patterns of technological change. They survey, integrate, and synthesize science, within and among scientific disciplines and across sectors and regions. Such scenarios are essential tools that enable projections of emissions, climate, vulnerabilities, and global change. They are indispensable for linking science and decision-making and for assessing choices about America's climate future.

Stakeholders and scientists within this assessment identified a need for more fully developed scenario-building capabilities that better enable assessments at regional and sectoral scales in timeframes of relevance to policy and decision-making and that more effectively reflect climate and global change at these scales.

Achieving capacity in scenario development will:

- **Enhance understanding of how and why climate may change and its implications,** especially at the regional scale. For example, a set of scenarios can be used to better understand the way energy, land use, and policy choices create alternative emissions pathways; how changes at global scales can be downscaled to estimate local climate possibilities; how various socioeconomic development pathways increase or decrease climate vulnerability; and to assess alternative strategies for reducing emissions and implementing adaptation; and

- **Develop new methods, tools, and skills for applying scenarios to policy development** at local levels in order to broaden society's understanding of a changing climate and to analyze the full range of policy choices. In addition, improve capabilities in integrated assessment modeling to inform policy analysis and allow stakeholders to co-produce information and explore options for local and national decisions.

5. Promote international research and collaboration

Research efforts in support of climate assessment are very dependent on the international research community. International teams conduct Earth system monitoring and analysis using observing systems that cannot be funded and maintained by any one country alone. Many of the impacts of climate change in the U.S. are closely linked to how climate affects other parts of the world. There is general understanding that impacts of climate change on U.S. socioeconomic systems are mediated or amplified through globally connected commodity chains and prices; more detailed research on climate change and its impacts elsewhere is needed to provide accurate assessments of what could happen to U.S. regional and local economies. The U.S. has the capacity to leverage investments in collaborative international climate and global change scientific research efforts, examples of which include IGBP (International Geosphere-Biosphere Programme), WCRP (World Climate Research Programme), DIVERSITAS (an international program of biodiversity science), IHDP (International Human Dimensions Programme) (as they evolve into or in affiliation with the new Future Earth program), and IGFA (International Group of Funding Agencies for Global Change Research).

Supporting international collaborative research will:

- **Contribute to international systems of data collection, monitoring, indicators, and modeling** that closely track and project changes in Earth system dynamics, climate, human drivers, and climate impacts that are needed for national and international assessments;

- **Assess the implications of climate change for globally shared common resources** such as the oceans, polar regions, and migratory species; and

- **Fill important gaps in understanding of how climate change in other countries** affects U.S. food, energy, health, manufacturing, and national security.

Conclusions

This chapter summarizes research recommendations across a broad range of topics – research that the assessment authors deem essential to support future assessments. The authors recognize that federal agencies and others are making progress on many of these research areas and that sustained assessment is included in the goals of the USGCRP.

While the research goals discussed in this chapter are not ranked, the objectives listed below can be used as criteria for prioritizing these activities. The nation's federal research investments in support of the sustained assessment strategy should be designed to enhance the nation's ability to limit climate-related risk and increase the utility of scientific understanding in supporting decisions.

- **Promote understanding of the fundamental behavior of the Earth's climate and environmental systems:** The consequences of climate variability and change will require enhanced investment in use-inspired research using both fundamental and applied analysis, providing a foundation for the nation's sustained assessment process;

- **Promote understanding of the socioeconomic impacts of a changing climate:** Provide comprehensive understanding, including the development of indicators of the impacts and consequences of climate variability and change for regions and sectors within the United States;

- **Build capacity to assess risks and consequences:** Support improved, timely, and accessible estimations and projections of climate and other global change risks, their consequences and relevance for stakeholders, associated costs and benefits, and interactions with other stresses;

- **Support research that enables infrastructure for analysis:** Sustain and enhance critical infrastructure, including observations and data essential to monitoring trends, projecting climate risks, and evaluating the effectiveness of responses in decision-making and policy implementation;

- **Build decision-support capacity:** Build the knowledge base essential for decision support including developing and evaluating climate mitigation and adaptation solutions, technology innovation, institutions, and behavioral change; and

- **Support engagement of the private sector and investment communities:** Develop strategies to leverage federal research investments by engaging the private sector more fully in research and technology development, including partnerships with the nation's universities and scientific research institutions, to address critical gaps in knowledge and to build the nation's future scientific, technical, and sustained assessment capacities.

- **Leverage private sector, university, and international resources and partnerships:** Take advantage of topics and expertise where the U.S. can leverage and complement private sector and university capabilities, obtain return on research investments, and lead internationally on research investment efforts; build capacity through education and training; support humanitarian response; and fill critical gaps in global knowledge of relevance to the United States.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Chapter Process:

The author team asked each of the other chapter author teams to identify important gaps in knowledge and key research needs in the course of writing their chapters, particularly in the context of the needs for research to support future assessments. In addition to the lists provided by each chapter author team, the team also drew on analyses from over 100 technical and public review suggestions and a wide variety of technical and scholarly literature, especially the U.S. Global Change Research Program's Strategic Plan[5] and the National Research Council's *America's Climate Choices* reports,[2,3,4,8,10] to compile a list of potential research needs. Using expert deliberation, including a number of teleconference meetings and email conversations among author team members, the author team agreed on high-priority research needs, organized under five research goals.

CHAPTER 30
SUSTAINED ASSESSMENT: A NEW VISION FOR FUTURE U.S. ASSESSMENTS

Convening Lead Authors

John A. Hall, U.S. Department of Defense

Maria Blair, Independent

Lead Authors

James L. Buizer, University of Arizona

David I Gustafson, Monsanto Company

Brian Holland, ICLEI – Local Governments for Sustainability

Susanne C. Moser, Susanne Moser Research & Consulting and Stanford University

Anne M. Waple, Second Nature and University Corporation for Atmospheric Research

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On the Web: http://nca2014.globalchange.gov/report/response-strategies/sustained-assessment

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A primary goal of the U.S. National Climate Assessment (NCA) is to help the nation anticipate, mitigate, and adapt to impacts from global climate change, including changes in climate variability, in the context of other national and global change factors. Since 1990, when Congress authorized the U.S. Global Change Research Program (USGCRP) through the Global Change Research Act[1] and required periodic updates on climate science and its implications, researchers from many fields have observed significant climate change impacts in every region of the United States. The accelerating pace of these changes (for example, the recent rapid reductions observed in the extent and thickness of Arctic sea ice), as well as scenario-based projections for future climate changes and effects, is articulated in this third NCA.

Based on recommendations stemming from the National Research Council (NRC), USGCRP in its most recent strategic plan[2] identified the rationale and benefits of implementing a sustained assessment process. In response, a vision for a new approach to assessments took shape as the third NCA report was being prepared. The vision includes an ongoing process of working to understand and evaluate the nation's vulnerabilities to climate variability and change and its capacity to respond. A sustained assessment, in addition to producing quadrennial assessment reports as required by law, recognizes that the ability to understand, predict, assess, and respond to rapid changes in the global environment requires ongoing efforts to integrate new knowledge and experience. It accomplishes this by: 1) advancing the science needed to improve the assessment process and its outcomes, building associated foundational knowledge, and collecting relevant data; 2) developing targeted scientific reports and other products that respond directly to the needs of federal agencies, state and local governments, tribes, other decision-makers, and end users; 3) creating a framework for continued interactions between the assessment partners and stakeholders and the scientific community; and 4) supporting the capacity of those engaged in assessment activities to maintain such interactions.

To provide decision-makers with more timely, concise, and useful information, a sustained assessment process would include both ongoing, extensive engagement with public and private partners and targeted, scientifically rigorous reports that address concerns in a timely fashion. A growing body of assessment literature has guided and informed the development of this approach to a sustained assessment.[3,4,5]

The envisioned sustained assessment process includes continuing and expanding engagement with scientists and other professionals from government, academia, business, and non-governmental organizations. These partnerships broaden the knowledge base from which conclusions can be drawn. In addition, sustained engagement with decision-makers and end users helps scientists understand what information society wants and needs, and it provides mechanisms for researchers to receive ongoing feedback on the utility of the tools and data they provide.

An ongoing process that supports these forms of outreach and engagement allows for more comprehensive and insightful evaluation of climate changes across the nation, including how decision-makers and end users are responding to these changes. The most thoughtful and robust responses to climate change can be made only when these complex issues, including the underlying science and its many implications for the nation, are documented and communicated in a way that both scientists and non-scientists can understand.

This sustained assessment process will lead to better outcomes for the people of the United States by providing more relevant, comprehensible, and usable knowledge to guide decisions related to climate change at local, regional, and national scales. Additional details about the components of the sustained assessment process are provided in "Preparing the Nation for Change: Building a Sustained National Climate Assessment Process," the first special report of the National Climate Assessment and Development Advisory Committee.[6]

Contributions of a Sustained Assessment Process

A sustained assessment process will not only include producing the quadrennial assessment reports required by the 1990 GCRA, but it also will enable many other important outcomes. A well-designed and executed sustained assessment process will:

1. Increase the nation's capacity to measure and evaluate the impacts of and responses to further climate change in the United States, locally, regionally, and nationally.
2. Improve the collection of assessment-related critical data, access to those data, and the capacity of users to work with datasets – including their use in decision support tools – relevant to their specific issues and interests. This includes periodically assessing how users are applying such data.

3. Support the creation of the first integrated suite of national indicators of climate-related trends across a variety of important climate drivers and responses.

4. Catalyze the production of targeted, in-depth special assessment reports on sectoral topics (for example, agriculture), cross-sectoral topics (for example, the connection between water and energy production), regional topics, and other topics that will help inform Americans' climate choices about mitigation and adaptation. These reports will generate new insights about climate change, its impacts, and the effectiveness of societal responses. In addition, a second report category, referred to as foundational reports, will focus on improvements to specific aspects of the process (for example, scenarios and indicators) to reinforce the foundation for the overarching, but necessarily more constrained, quadrennial assessment reports.

5. Facilitate the creation of, support, and leverage a network of scientific, decision-maker, and user communities for extended dialog and engagement regarding climate change.

6. Provide a systematic way to identify gaps in knowledge and uncertainties faced by the scientific community and by U.S. domestic and international partners and to assist in setting priorities for their resolution.

7. Enhance integration with other assessment efforts such as the Intergovernmental Panel on Climate Change and modeling efforts such as the Coupled Model Intercomparison Project.

8. Develop and apply tools to evaluate progress and guide improvements in processes and products over time. This will support an iterative approach to managing risks and opportunities associated with changing global and national conditions.

Assessments facilitate the collection of different kinds of information that can be integrated to yield new and useful scientific insights. The vision for the sustained assessment process is to continue to build knowledge about human and natural systems and their interactions to better understand the risks and opportunities of global change at multiple spatial and temporal scales. The sustained assessment process also can help define the range of information needs of decision-makers and end users relative to adaptation and mitigation, as well as the associated costs of impacts and benefits of response actions. Moreover, it is by its very nature a continuous process, uniquely positioned to support an iterative, risk-based approach to adaptation.

Finally, although a sustained assessment process allows for ongoing improvements in products and processes, it also requires underlying support systems. These can include access to observational data sources, support networks, and information management systems such as the Global Change Information System (GCIS; see section on "Data Collection, Access, and Analysis"). Other fundamental support for assessments includes various types of integrated and vulnerability assessment models, climate model intercomparison projects, data streams (for example, emissions data and socioeconomic data), processes for building scenarios and deploying them at critical junctures in the assessment process, and evaluation approaches.

Assessment Capacity

Scientific assessments require substantial scientific expertise and judgment, involving skills atypical of those required for routine research.[4,5] Assessment capacity includes engaging knowledgeable and experienced people, developing networks to promote interactions, identifying and mentoring new scientific talent, and building in-depth understanding of a variety of economic, technical, and scientific topics. Building and maintaining capacity through all of these approaches is therefore critical to the smooth and efficient functioning of the assessment process.

Sustained interactions among scientists and stakeholders have consistently been shown to improve the utility and effectiveness of assessment processes and outcomes[5] and to facilitate the development of decision support tools.[7] A sustained assessment provides the necessary coordination and infrastructure needed to maintain an ongoing dialog among producers and users of information so that decision-makers can manage risks and take advantage of opportunities more efficiently. This provides the capacity and flexibility to react to, and take advantage of, rapidly advancing developments in decision and climate science and changing conditions to inform robust decision-making and improve the utility and timeliness of future quadrennial assessment reports.

Data Collection, Access, and Analysis

Credible scientific information is needed on an ongoing basis to support fundamental understanding of the climate system and its interactions with ecological, economic, and social systems – and for the development of adaptation and mitigation strategies. Improved systems for data access can more effectively meet the requests of stakeholders for accessible, relevant, and timely information. An ongoing process can build a more complete information base relevant to climate change related impacts and vulnerabilities, and it can result in more sophisticated scientific analyses that support the mandated quadrennial assessment reports in a more efficient and effective manner. Selecting which data to collect and analyze is a critical component of assessments of change. In addition, for certain assessment-related purposes, use of traditional knowledge may be appropriate and require different analytical approaches.

The sustained assessment process will facilitate the development and maintenance of a web-based assessment information discovery, access, and retrieval system that facilitates easy access to a range of information for those who need it, in a timely and authoritative manner (the GCIS of the USGCRP). A major short-term goal is to provide transparent and highly-linked access to the data used to support conclusions in the third NCA report, but this is only the first step in a much larger effort. Initially targeted audiences include assessment practitioners across various sectors and governmental levels.

Indicators

Indicators are measurements or calculations that represent important features of the status, trends, or performance of a system (such as the economy, agriculture, natural ecosystems, or Arctic sea ice cover). Indicators are used to identify and communicate changing conditions to inform both research and management decisions.[8] The NCA indicator system is intended to focus on key aspects of change – as well as vulnerabilities, impacts, and states of preparedness – to inform decision-makers and the public. In the context of ongoing assessment activities, these indicators can be tracked to provide timely, authoritative, and climate-relevant measurements regarding the status, rates of change, and trends of key physical, ecological, and societal variables.

Special and Foundational Reports

As currently envisioned, the sustained assessment process also paves the way for additional types of assessment-related reports that can help inform local, regional, and sectoral mitigation and adaptation activities and provide a foundation for more useful and more comprehensive quadrennial assessment reports. Completing in-depth assessments of national or regional importance and providing a constantly improving foundation for the quadrennial assessment reports provides for significant flexibility and enhanced policy relevance. Special topical assessment reports can investigate emerging issues of concern or help decision-makers understand the tradeoffs among different courses of action. Moreover, these types of assessments can encompass a more holistic, multi-disciplinary, and integrated approach that considers various types of data analyses that may not have been previously attempted. These more focused reports that emerge from ongoing assessment activities can blend the objectives of incorporating the latest science with responding relatively quickly to the most pressing stakeholder and government needs. Finally, foundational reports also can be produced on scenarios of climate change, sea level rise, demography, land-use change, and other issues critical to the assessment process.

A Network to Foster Partnerships, Encourage Engagement, and Develop Solutions

The USGCRP has long recognized the importance of partnerships, effective two-way communication, and ongoing and meaningful engagement.[2] The five NRC *America's Climate Choices* reports published in 2010 and 2011 also underscore the essential nature of this engagement (for example, NRC 2010[9]). Partnerships and engagement strategies among federal and non-federal participants are needed to: 1) communicate effectively about the assessment, including its products and processes and their relevance as actionable information;[10] 2) encourage participation and knowledge sharing; 3) create opportunities for meaningful engagement of end users and public and private decision-makers to inform the substance of the assessment; and 4) offer opportunities for input, direction, review, and feedback.

An important component of the new sustained assessment vision is NCAnet: a "network of networks" that helps to foster engagement in the NCA process and communicate products to a broader audience (for additional details about NCAnet, please see Appendix 1: Process). This network of partner organizations, including private sector, government, non-governmental organizations, and professional societies, leverages resources and facilitates communication and partnerships. By its first meeting in January 2012, NCAnet consisted of over three dozen partner organizations. Much of the network's subsequent growth to over 100 partner organizations (as of fall 2013) has been driven by the partners' own outreach and interest in building a community around the practice of assessment. NCAnet can assist in developing and supporting diverse science capabilities and assessment competencies within and outside of the Federal Government.

Evaluation of the Process

Ongoing evaluation of assessment processes and products, as well as incorporating the lessons learned over time, is a specific objective of the USGCRP Strategic Plan.[2] Evaluation efforts are considered integral to enabling learning and adaptive management of the assessment process, measuring the ability to meet both legally required objectives and strategic goals, maintaining institutional memory, and improving the assessment process and its contributions to scientific understanding as well as to society. Ongoing improvements in the assessment process also will support an iterative approach to decision-making in the context of rapid change.

Recommendations on Research Priorities

The GCRA requires regular evaluations of gaps in knowledge and assessments of uncertainties that require additional scientific input. A sustained assessment process provides for regular updates on science needs to the USGCRP's annual research prioritization process, as well as to the triennial and decadal revisions to its research plan.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

Planning for the sustained assessment process, and for including a description of the process in a chapter of the third NCA report, began as soon as the report process was launched. Mechanisms for creating and implementing a sustained process were included as key discussion points in early NCA process workshops.[11] Prior to the formation of the chapter author teams, the need for a sustained assessment was described in the NCA Strategy Summary.[12] The amended charter for the National Climate Assessment and Development Advisory Committee (NCADAC) specifies that the NCADAC is "to provide advice and recommendations toward the development of an ongoing, sustainable national assessment of global change impacts and adaptation and mitigation strategies for the Nation."[13] To that end, the NCADAC formed a working group on sustained assessment, and the USGCRP Interagency National Climate Assessment Working Group (INCA) made this topic a priority in their regular meetings. The USGCRP also established "conduct sustained assessments" as one of four programmatic pillars in its recent Strategic Plan.[2]

The sustained assessment author team drew on a wide variety of source materials in framing the need for a sustained assessment process, including calls for sustained assessment in both previous National Climate Assessment reports[14] and in several publications from the National Research Council[5,9,15] that focused specifically on the National Climate Assessment. The author team also considered a rich literature on assessments in general (for example, Farrell and Jäger 2005 and Mitchell et al. 2006[4]). In developing the chapter describing the sustained assessment process, the author team first worked with the NCADAC, especially the initial NCADAC working group on sustained assessment, and the INCA to develop a vision for sustained assessment and a list of activities required to implement this vision. They then collected feedback from each of the chapters' convening lead authors, agencies, chairs of other NCADAC working groups, and targeted stakeholders. Drawing on these comments and the knowledge bases cited above, the author team came to consensus on the objectives and categories of activities provided in the chapter through teleconference and email discussions. The NCADAC formed a new author team to produce a longer special report on the sustained assessment process. The report was completed in the late summer of 2013.[6]

APPENDIX 1 REPORT DEVELOPMENT PROCESS

The National Climate Assessment (NCA) supports the U.S. Global Change Research Program (USGCRP) and its Strategic Plan[1] in multiple ways. The Strategic Plan focuses on climate science that informs societal objectives; the USGCRP program and the NCA help build an information base to support climate-related decisions, including decisions to reduce human contributions to future climate change, and to adapt to changes that are occurring now and are projected in the future. In order to facilitate the integration of federal science investments with academic, public, and private sector climate change research, the Third NCA process focused on building strong relationships with stakeholders and experts outside the government. Early in the process, the National Climate Assessment and Development Advisory Committee (NCADAC) and NCA Coordination Office developed a strategy to engage a broad range of the American public. Open participation, communication, and feedback have been integral to the preparation of this far-reaching assessment.[2]

NCA Goal and Vision

As established by the NCADAC,[3] the overarching goal of the NCA process is to enhance the ability of the United States to anticipate, mitigate, and adapt to changes in the global environment that are increasingly linked to human activities.

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

Legislative Foundations

The NCA is conducted under the auspices of the Global Change Research Act (GCRA) of 1990.[4] The mandate for the U.S. Global Change Research Program as a whole is: “To provide for development and coordination of 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.”

Section 106 of the GCRA requires a report to the President and the Congress every four years that integrates, evaluates, and interprets the findings of the USGCRP; 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 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 federation of the research components of 13 federal departments and agencies that supports the largest investment in climate and global change research in the world. USGCRP coordinates research activities across agencies and establishes joint funding priorities for research. USGCRP’s Strategic Plan, adopted in 2012, focuses on four major goals: advance science, inform decisions, conduct sustained assessments, and communicate and educate.[1] The USGCRP agencies maintain and develop observations, monitoring, data management, analysis, and modeling capabilities that support the nation’s response to global change. The agencies that comprise the USGCRP are:

U.S. Department of Agriculture
U.S. Department of Commerce
U.S. Department of Defense
U.S. Department of Energy
U.S. Department of Health & Human Services
U.S. Department of the Interior
U.S. Department of State
U.S. Department of Transportation
U.S. Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation
The Smithsonian Institution
U.S. Agency for International Development

The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities. SGCR operates under the direction of the National Science and Technology Council's (NSTC) Committee on Environment, Natural Resources, and Sustainability (CENRS) 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 interagency working groups (IWGs).

National Climate Assessment (NCA) Components

The **Interagency NCA Working Group (INCA)** is comprised of representatives of the 13 government agencies listed above, plus additional agencies that have chosen to engage in supporting the NCA activities. INCA is responsible for coordinating, developing, and implementing interagency activities for the NCA, providing critical input to identify and support future NCA products, and developing interagency assessment capacity at the national and regional scales. Through INCA, the agencies have supported the development of the 30 chapters and the process to create the Third NCA report in a variety of ways.

The **National Climate Assessment and Development Advisory Committee (NCADAC)** is a 60-member federal advisory committee established by the Department of Commerce on behalf of USGCRP. Forty-four non-federal NCADAC members represent the public, private, and academic sectors; 16 non-voting ex-officio members represent the USGCRP agencies, the Department of Homeland Security, the SGCR, and the White House Council on Environmental Quality. The NCADAC charter charges the group with developing the Third NCA report and with providing recommendations about how to sustain an ongoing assessment process. The NCADAC selected the authors of the individual chapters and coordinated many of the assessment activities leading to this report. This included NCADAC meetings and more than 20 NCADAC subcommittee working groups on specific assessment needs (for example, regional and sectoral integration, engagement and communication, indicators, and international linkages). An Executive Secretariat of 12 individuals (a subset of the full committee) helps to coordinate the activities of the full committee.

The **NCA Coordination Office** is a part of the USGCRP National Coordination Office in Washington, D.C. The office is supported and funded through an interagency agreement with the University Corporation for Atmospheric Research (UCAR). A team of UCAR staff and federal detailees (agency employees as-

Organization of NCA components

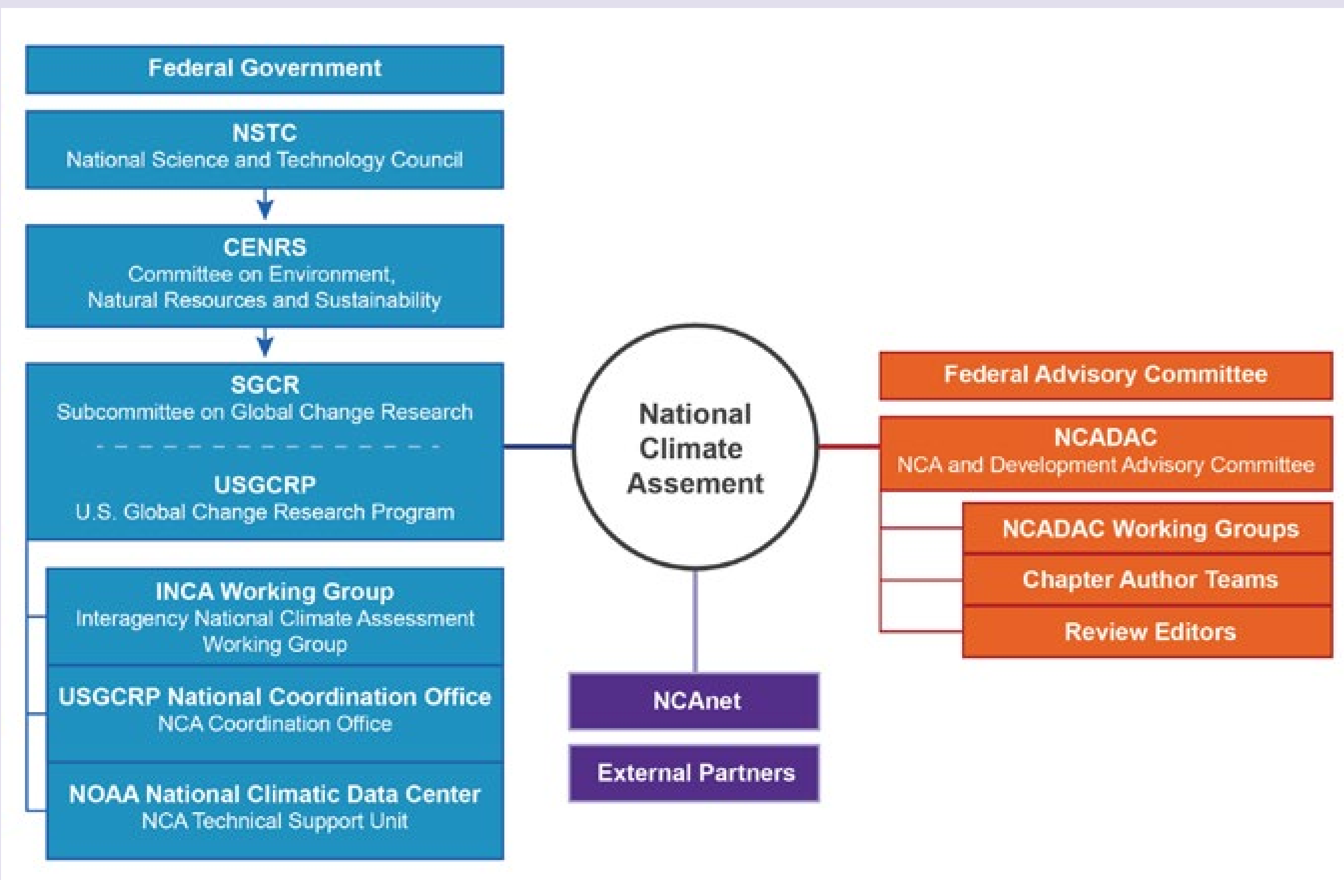

Figure 1.

signed to the NCA Coordination Office) with expertise in planning, writing, and coordinating collaborative climate and environmental science and policy activities provides support for the development of the NCA report and sustained assessment.

The **NCA Technical Support Unit (TSU)** is funded by the National Oceanic and Atmospheric Administration (NOAA) and is located at NOAA's National Climatic Data Center in Asheville, NC. The TSU staff provides multiple kinds of support to the NCA, including climate science research, data management, web design, graphic design, technical and scientific writing and editing, publication production, and meeting support.

The **National Climate Assessment Network (NCAnet)** consists of more than 100 partner organizations that work with the NCA Coordination Office, NCADAC, report authors, and USGCRP agencies to engage producers and users of assessment information.[5] Partners extend 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 inputs into 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 its report findings.

Creating the Third NCA Report

Process Development

The NCA Engagement Strategy provides a vision for participation, outreach, communication, and education processes that help make the NCA process and products accessible and useful to a wide variety of audiences. The overall goal of engagement is to create a more effective and successful NCA – improving the processes and products of the effort so that they are credible, salient, and legitimate and building the capacity of participants to engage in the creation and use of NCA products in decision-making.[2] 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.

As part of the assessment process, a series of 14 process workshops helped establish consistent assumptions and methodologies. The resulting reports provide a consistent foundation for the technical input teams and chapter authors.

The NCA Coordination Office organized listening sessions, symposia, and sessions at professional society meetings during the development of the NCA report and sustained assessment process. These sessions provided updates on the NCA process, solicited broad input from subject matter experts, and collected feedback on the approach, topics, and methodologies under consideration.

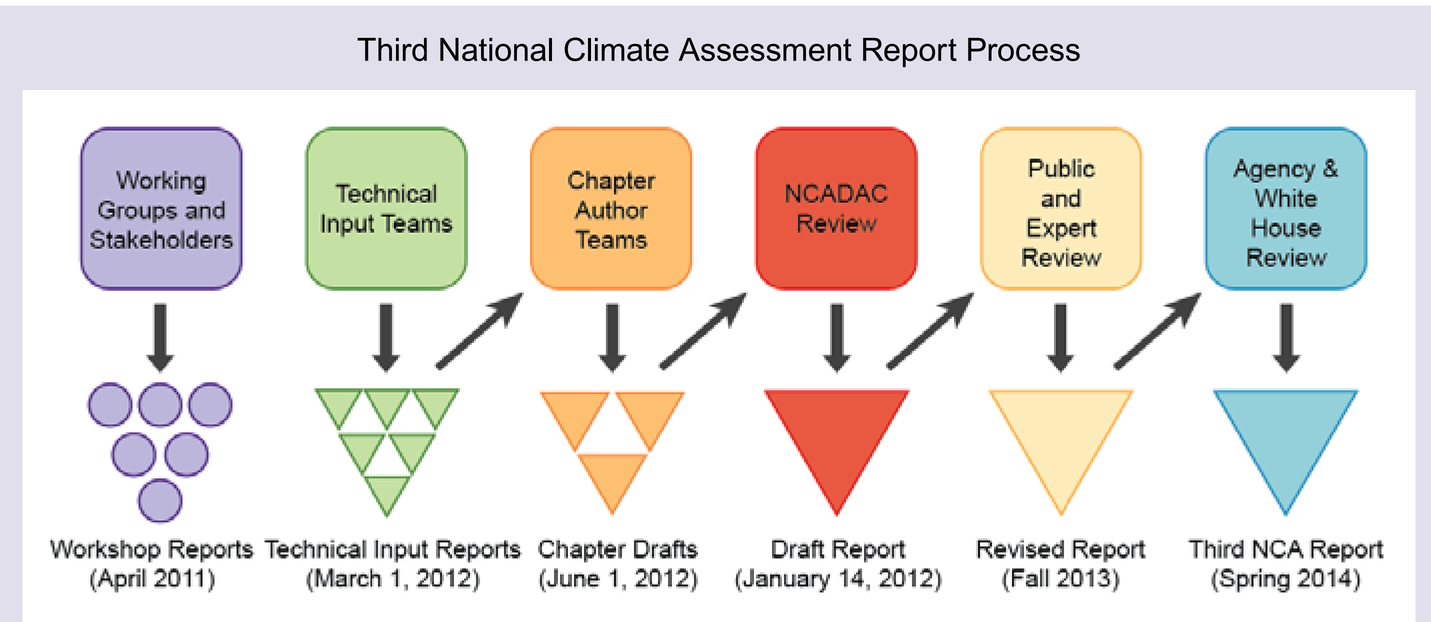

Figure 2. This graphic illustrates the activities and products that were developed during the Third NCA report development process.

Technical Input Reports

A public Request for Information[6] resulted in submission of more than 500 technical input documents authored by more than 800 individuals from academia, industry, and government, including 25 technical inputs[7] sponsored by USGCRP agencies. These inputs included documents and data sets for review and consideration by the author teams that developed the NCA report. Technical input authors used a variety of mechanisms to engage stakeholders in the scoping, writing, and review of their documents, including workshops, web-based seminars, and public comment periods, among other methods.

In addition, the Technical Support Unit climate science team developed nine peer-reviewed regional climate scenario documents (one for each of the eight regions and one for the contiguous United States),[8] providing a scientific consensus view of historical climate trends and projections under the IPCC Special Report on Emissions Scenarios (SRES) A2 and B1 scenarios.[9] A separate interagency committee developed four peer-reviewed sea level rise scenarios.[10] These scenarios were used by chapter authors as underpinnings for their impact assessments.

Third NCA Report Draft Development and Review

The NCADAC selected two to three convening lead authors and approximately six lead authors for each chapter, based on criteria that included expertise, experience, geography, and ensuring a variety of perspectives. They included authors from the public and private sectors, non-governmental organizations, and universities. Beginning in December 2011, each of the author teams met multiple times by phone, web, and in person to produce and refine drafts of their chapters. Traceable accounts developed for each chapter provide transparent information about the authors' decision processes, scientific certainty, and their level of confidence related to the key findings of their respective chapters. All authors served in a volunteer capacity.

After reviewing the draft Third NCA report, the NCADAC released it for public review and comment on January 14, 2013.[11] Concurrently, the NCA underwent an independent expert review by the National Research Council, a part of the National Academies. A three-month review period allowed individuals and groups to examine the draft and provide comments aimed at improvement. The comments were provided using a secure online comment system to ensure that all comments were captured and appropriately addressed.

Regional town hall meetings, conducted by the NCA Coordination Office (one per region, plus coasts) and by NCAnet partners (three additional meetings), brought together authors, NCADAC members, and members of the public to discuss the NCA process and encourage participants to submit comments on the draft report. Report authors, NCADAC members, NCA staff, and NCAnet partners organized, spoke at, and participated in sessions at professional society meetings, web-based seminars, community meetings, and other events similarly aimed at providing an overview of the draft report and encouraging comments.[12]

By the time the public comment period closed on April 12, 2013, the online comment system received 4,161 comments from 644 government, non-profit, and commercial sector employees, educators, students, and the general public. Chapter author teams and the NCADAC amended the draft report in response to comments and prepared written responses to each comment received, and external review editors evaluated the adequacy of the responses to the comments on each chapter. As the result of a NCADAC consensus decision, the entire review process was "blind", that is, NCADAC members and authors did not know the identity of commenters when responding to each comment. The public comments (including commenters' identities) and the chapter authors' responses to those comments were posted online with the final report.
The National Research Council provided a second review of the report, and the NCADAC considered this review in developing a final draft for submission to federal agencies for review in fall 2013.

NCA Final Report

Any adjustments to the NCADAC's Fall 2013 draft as a result of the government review process were made with the authors' approval, and the NCADAC approved the final form of the report in Spring 2014. Having been accepted and finalized following government review, the report is now provided as the assessment by the Federal Government of the United States, pursuant to the requirements of the Global Change Research Act. A number of products derived from the report support the outreach activities following the report release.

Engagement Activities

What follows is a sample of activities convened in support of the development of the Third NCA Report. A full list of activities is available online at http://assessment.globalchange.gov.
NCADAC Meetings: All meetings were open the public. The presentations, documents, and minutes for each NCADAC meeting are available online at http://www.nesdis.noaa.gov/NCADAC/Meetings.html.

- April 4-6, 2011, Washington, DC http://www.nesdis.noaa.gov/NCADAC/April_4_Meeting.html
- May 20, 2011, Teleconference
- August 16-18, 2011, Arlington, VA

- November 16-17, 2011, Boulder, CO
- April 10, 2012, Teleconference
- June 14-15, 2012, Washington, DC
- August 15, 2012, Teleconference
- September 27, 2012, Teleconference
- November 14-15, 2012, Silver Spring, MD
- January 11, 2013, Teleconference
- May 13, 2013, Teleconference
- July 9-10, 2013, Washington, DC
- November 18, 2013, Teleconference
- February 20-21, 2014, Washington, DC
- Spring 2014, Final approval of the Third NCA via teleconference

Process and Methodology Workshops: Reports from these workshops are available online at http://www.globalchange.gov/what-we-do/assessment/nca-activities/workshop-and-meeting-reports.

- Midwest Regional Workshop, February 2010, Chicago, IL
- Strategic Planning Workshop, February 2010, Chicago, IL
- Scoping the Product(s) and Work Plan for the Third National Assessment, June 2010, Washington, DC [no report available]
- Communications Scoping Meeting, July 2010, Washington, DC [no report available]
- International Scoping Meeting, August 2010, Washington, DC [no report available]
- Knowledge Management Workshop, September 2010, Reston, VA
- Regional Sectoral Workshop, November 2010, Reston, VA
- Ecological Indicators Workshop, November 2010, Washington, DC
- Scenarios Workshop, December 2010, Arlington, VA
- Climate Change Modeling and Downscaling Workshop, December, 2010, Arlington, VA
- Valuation Techniques and Metrics Workshop, January 2011, Arlington, VA
- Vulnerability Assessments Workshop, January 2011, Atlanta, GA
- Physical Climate Indicators Workshop, March 2011, Washington, DC
- Societal Indicators Workshop, April 2011, Washington, DC

Agency-Sponsored Technical Input Development Workshops

- Monitoring Changes in Extreme Storm Statistics: State of Knowledge, July 2011, Asheville, NC
- Forestry Sector Stakeholder Workshop, July 2011, Atlanta, GA
- Land Use and Land Cover Stakeholder Workshop, November 1011, Salt Lake City, UT
- Energy Supply and Use Workshop, November 2011, Washington, DC
- Energy, Water, Land Planning Meeting, November 2011, Washington, DC
- Urban Infrastructure and Vulnerabilities Workshop, November 2011, Washington, DC
- Trends and Causes of Observed Changes in Heat Waves, Cold Waves, Floods, and Drought, Nov. 2011, Asheville, NC
- Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts, January 2012, Asheville, NC
- Ecosystems, Biodiversity, and Ecosystem Services Workshop, January 2012, Palo Alto, CA
- Water Sector Technical Input Workshop, January 2012, Washington, DC
- Coastal Zone Stakeholders Meeting, January 2012, Charleston, SC
- Climate Change and Health Workshop - Southeast, February 2012, Charleston, SC
- Rural Communities Workshop, Feb. 2012, Charleston SC
- Climate Change and Health Workshop - Northwest, February 2012, Seattle, WA

Listening Sessions

- Annual Meeting of the Association of American Geographers, April 2011, Seattle, WA
- American Water Resource Association Spring Specialty Conference, April 2011, Baltimore, MD
- International Symposium on Society and Resource Management, June 2011, Madison, WI
- Annual Soil and Water Conservation Society Conference, July 2011, Washington, DC
- Ecological Society of America Annual Meeting, August 2011, Austin, TX
- American Meteorological Society Annual Meeting, January 2012, New Orleans, LA

Regional Town Hall Meetings

- Hawai‘i & Pacific Islands Town Hall, December 2012, Honolulu, HI
- Southwest Regional Town Hall, January 2013, San Diego, CA
- Northeast Regional Town Hall, January 2013, Syracuse, NY
- Great Plains Regional Town Hall, February 2013, Lincoln, NE
- Alaska Regional Town Hall, February 2013, Anchorage, AK
- Midwest Regional Town Hall, February 2013, Ann Arbor, MI
- Southeast Regional Town Hall, February 2013, Tampa, FL
- Northwest Regional Town Hall, March 2013, Portland, OR
- Oceans and Coasts Town Hall, April 2013, Washington, DC

NCAnet Partners Activities

The NCAnet Partners meet monthly (since January 2012) in Washington, DC; teleconference and web conference capabilities allow participants to join remotely. NCAnet Partners hosted more than 25 events around the country for the public and stakeholders throughout the NCA process. A list of partners, minutes from meetings, and a list of events and resulting products is available at http://ncanet.usgcrp.gov.

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APPENDIX 2 INFORMATION QUALITY ASSURANCE PROCESS

Summary of Information Quality Assurance Process for the Third National Climate Assessment Report

Throughout the process of drafting this National Climate Assessment, guidance was provided to contributors, authors, federal advisory committee members, and staff regarding the requirements of the Information Quality Act (IQA).

In September 2011, *Preliminary Guidance on Information Quality Assurance in Preparing Technical Input for the National Climate Assessment (NCA)*[1] was made available on the U.S. Global Change Research Program's (USGCRP) website along with other information for those interested in submitting technical input to the NCA in response to the Request for Information posted in the Federal Register on July 13, 2011.[2] This frequently asked questions-style document provided preliminary guidance regarding information quality for use by teams who submitted Expressions of Interest and Technical Inputs for use in the NCA.

In November 2011, the National Climate Assessment and Development Advisory Committee (NCADAC) approved the *General Principles Used in the Development of Guidance for Assuring Information Quality in the National Climate Assessment*.[3] The *Principles* were used by the NCADAC to draft guidance for all Convening Lead Authors (CLAs), Lead Authors, Review Editors, NCADAC, and Government Agencies and Reviewers to assure that information used in the NCA production was of appropriate quality relative to its intended use.

Two tools were developed – a set of questions and a flowchart – to assist the authors and reviewers in determining whether and how to use potential source material in the NCA within the requirements of the IQA. These tools (collectively, *Guidance on Information Quality Assurance to Chapter Authors of the National Climate Assessment: Question Tools*) were approved by the NCADAC and introduced to the CLAs at workshops. They have been available on the USGCRP website since February 2012.[4] The *Guidance* requires consideration of the following criteria for each source of information used in the Third NCA Report:

- 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?

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APPENDIX 3 CLIMATE SCIENCE SUPPLEMENT

Convening Lead Authors

John Walsh, University of Alaska Fairbanks

Donald Wuebbles, University of Illinois

Lead Authors

Katharine Hayhoe, Texas Tech University

James Kossin, NOAA National Climatic Data Center

Kenneth Kunkel, CICS-NC, North Carolina State Univ., NOAA National Climatic Data Center

Graeme Stephens, NASA Jet Propulsion Laboratory

Peter Thorne, Nansen Environmental and Remote Sensing Center

Russell Vose, NOAA National Climatic Data Center

Michael Wehner, Lawrence Berkeley National Laboratory

Josh Willis, NASA Jet Propulsion Laboratory

Contributing Authors

David Anderson, NOAA National Climatic Data Center

Viatcheslav Kharin, Canadian Centre for Climate Modelling and Analysis, Environment Canada

Thomas Knutson, NOAA Geophysical Fluid Dynamics Laboratory

Felix Landerer, Jet Propulsion Laboratory

Tim Lenton, Exeter University

John Kennedy, UK Meteorological Office

Richard Somerville, Scripps Institution of Oceanography, Univ. of California, San Diego

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On the Web: http://nca2014.globalchange.gov/report/appendices/climate-science-supplement

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

APPENDIX 3 CLIMATE SCIENCE

Supplemental Messages

1. **Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.**

2. **Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.**

3. **Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.**

4. **Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.**

5. **Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.**

6. **Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.**

7. **Scientific understanding of observed temperature changes in the United States has greatly improved, confirming that the U.S. is warming due to heat-trapping gas emissions, consistent with the climate change observed globally.**

8. **Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.**

9. **Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate change's effects on other types of extreme events continues.**

10. **Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.**

11. Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

12. Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

This appendix provides further information and discussion on climate science beyond that presented in Ch. 2: Our Changing Climate. Like the chapter, the appendix focuses on the observations, model simulations, and other analyses that explain what is happening to climate at the national and global scales, why these changes are occurring, and how climate is projected to change throughout this century. In the appendix, however, more information is provided on attribution, spatial and temporal detail, and physical mechanisms than could be covered within the length constraints of the main chapter.

As noted in the main chapter, changes in climate, and the nature and causes of these changes, have been comprehensively discussed in a number of other reports, including the 2009 assessment: *Global Climate Change Impacts in the United States*[1] and the global assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Academy of Sciences. This appendix provides an updated discussion of global change in the first few supplemental messages, followed by messages focusing on the changes having the greatest impacts (and potential impacts) on the United States. The projections described in this appendix are based, to the extent possible, on the CMIP5 model simulations. However, given the timing of this report relative to the evolution of the CMIP5 archive, some projections are necessarily based on CMIP3 simulations. (See Supplemental Message 5 for more on these simulations and related future scenarios).

Supplemental Message 1.

Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.

The Earth's climate has long been known to change in response to natural external forcings. These include variations in the energy received from the sun, volcanic eruptions, and changes in the Earth's orbit, which affects the distribution of sunlight across the world. The Earth's climate is also affected by factors that are internal to the climate system, which are the result of complex interactions between the atmosphere, ocean, land surface, and living things (see Supplemental Message 3). These internal factors include natural modes of climate system variability, such as the El Niño/Southern Oscillation.

Natural changes in external forcings and internal factors have been responsible for past climate changes. At the global scale, over multiple decades, the impact of external forcings on temperature far exceeds that of internal variability (which is less than 0.5°F).[2] At the regional scale, and over shorter time periods, internal variability can be responsible for much larger changes in temperature and other aspects of climate. Today, however, the picture is very different. Although natural factors still affect climate, human activities are now the primary cause of the current warming: specifically, human activities that increase atmospheric levels of carbon dioxide (CO_2) and other heat-trapping gases and various particles that, depending on the type of particle, can have either a heating or cooling influence on the atmosphere.

The greenhouse effect is key to understanding how human activities affect the Earth's climate. As the sun shines on the Earth, the Earth heats up. The Earth then re-radiates this heat back to space. Some gases, including water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), absorb some of the heat given off by the Earth's surface and lower atmosphere. These heat-trapping gases then radiate energy back toward the surface, effectively trapping some of the heat inside the climate system. This greenhouse effect is a natural process, first recognized in 1824 by the French mathematician and physicist Joseph Fourier[3] and confirmed by British scientist John Tyndall in a series of experiments starting in 1859.[4] Without this natural greenhouse effect (but assuming the same albedo, or reflectivity, as today), the average surface temperature of the Earth would be about 60°F colder.

Today, however, the natural greenhouse effect is being artificially intensified by human activities. Burning fossil fuels (coal, Human Influence on the Greenhouse Effect

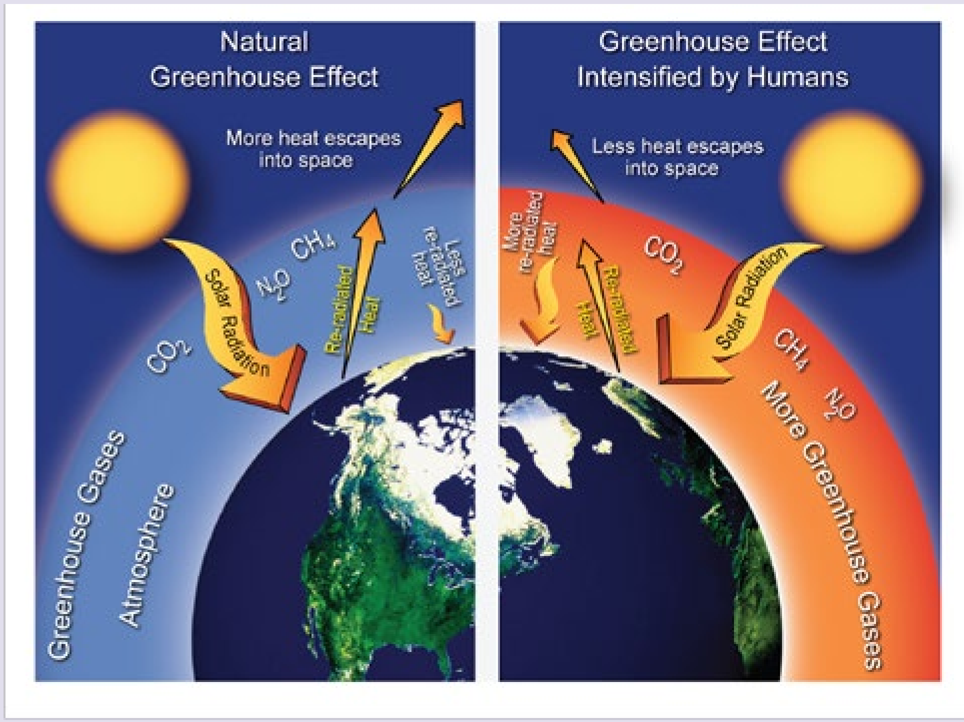


Figure 1. Left: A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. **Right**: In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service[5]).

Earth's Energy Balance

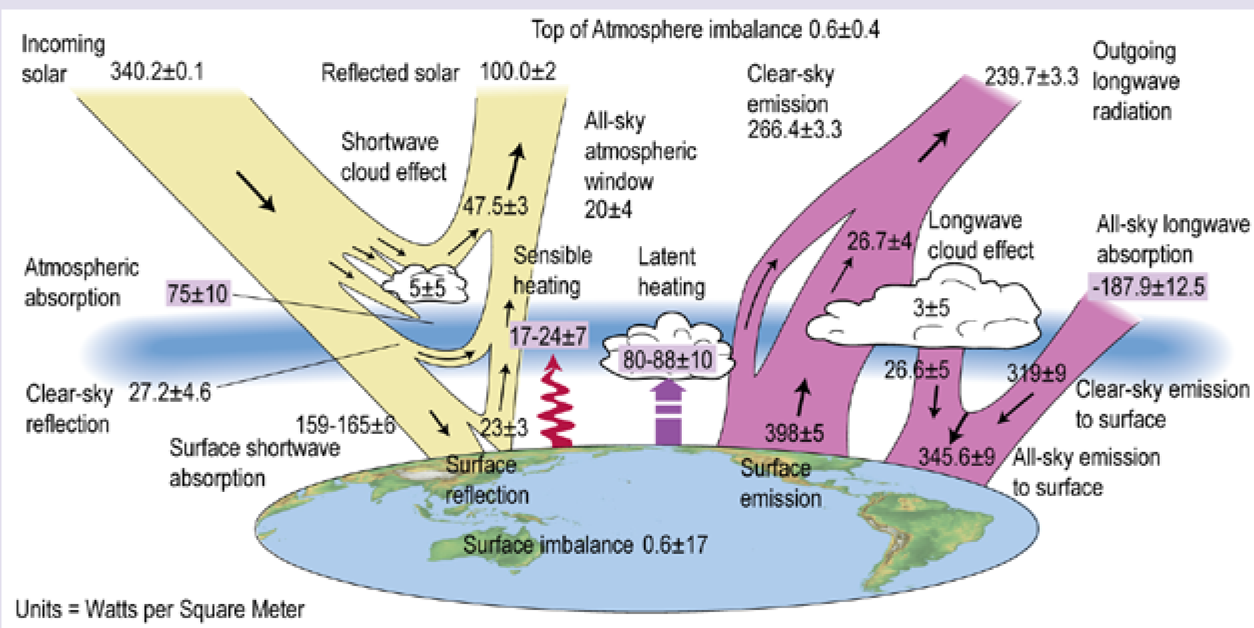


Figure 2. This figure summarizes results of measurements taken from satellites of the amount of energy coming in to and going out of Earth's climate system. It demonstrates that our scientific understanding of how the greenhouse effect operates is, in fact, accurate, based on real world measurements. (Figure source: modified from Stephens et al. 2012[6]).

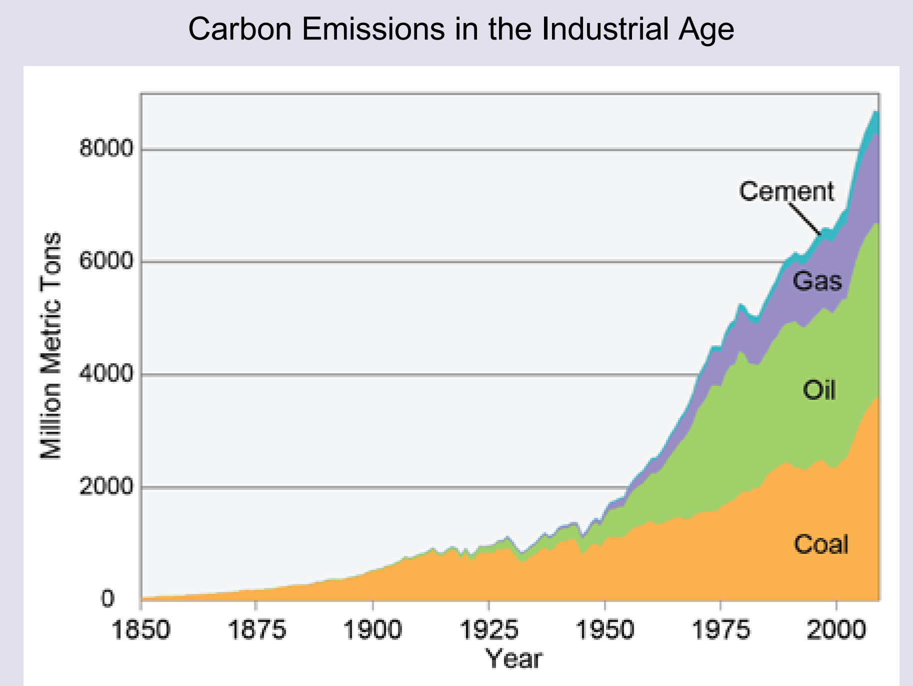


Figure 3. Global carbon emissions from burning coal, oil, and gas and producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades (Data from Boden et al. 2012[7]).

oil, and natural gas), clearing forests, and other human activities produce heat-trapping gases. These gases accumulate in the atmosphere, as natural removal processes are unable to keep pace with increasing emissions. Increasing atmospheric levels of CO_2, CH_4, and N_2O (and other gases and some types of particles like soot) from human activities increase the amount of heat trapped inside the Earth system. This human-caused intensification of the greenhouse effect is the primary cause of observed warming in recent decades.

Carbon dioxide has been building up in the Earth's atmosphere since the beginning of the industrial era in the mid-1700s. Emissions and atmospheric levels, or concentrations, of other important heat-trapping gases – including methane, nitrous oxide, and halocarbons – have also increased because of human activities. While the atmospheric concentrations of these gases are relatively small compared to those of molecular oxygen or nitrogen, their ability to trap heat is extremely strong. The human-induced increase in atmospheric levels of carbon dioxide and other heat-trapping gases is the main reason the planet has warmed over the past 50 years and has been an important factor in climate change over the past 150 years or more.

Carbon dioxide levels in the atmosphere are currently increasing at a rate of 0.5% per year. Atmospheric levels measured at Mauna Loa in Hawai'i and at other sites around the world reached 400 parts per million in 2013, higher than the Earth has experienced in over a million years. Globally, over the past several decades, about 78% of carbon dioxide emissions has come from burning fossil fuels, 20% from deforestation and other agricultural practices, and 2% from cement production. Some of the carbon dioxide emitted to the atmosphere is absorbed by the oceans, and some is absorbed by vegetation.

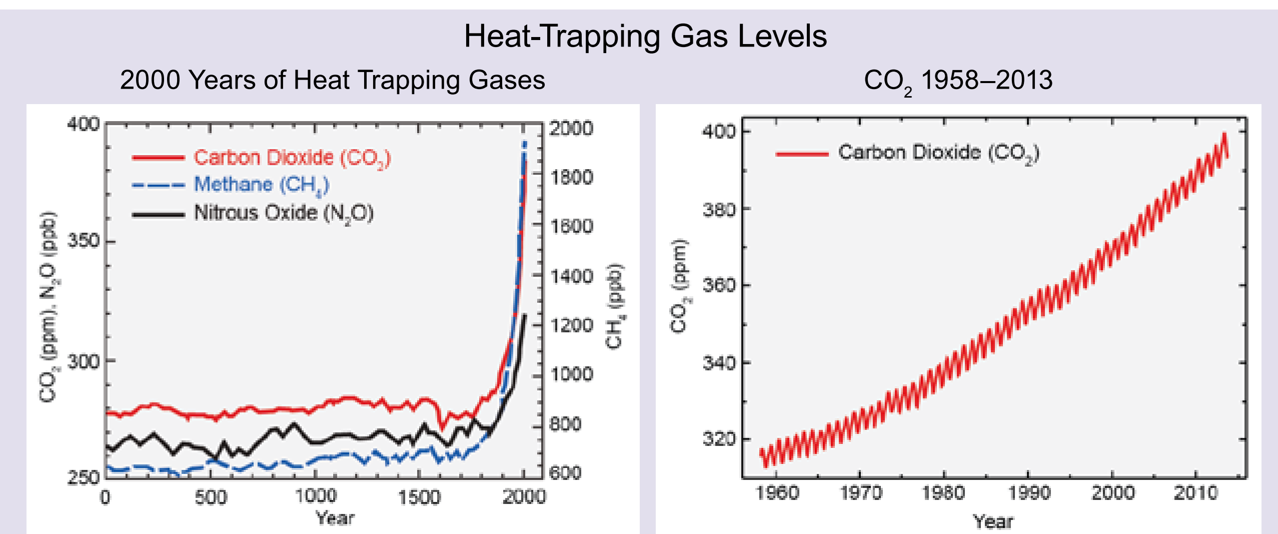


Figure 4. Present-day atmospheric levels of carbon dioxide, methane, and nitrous oxide are notably higher than their pre-industrial averages of 280, 0.7, and 0.27 parts per million (ppm) by volume, respectively (left). Air sampling data from 1958 to 2013 show long-term increases due to human activities as well as short-term variations due to natural biogeochemical processes and seasonal vegetation growth (right). (Figure sources: (left) Forster et al. 2007;[8] (right) Scripps Institution of Oceanography and NOAA Earth Systems Research Laboratory).

Atmospheric Carbon Dioxide Levels

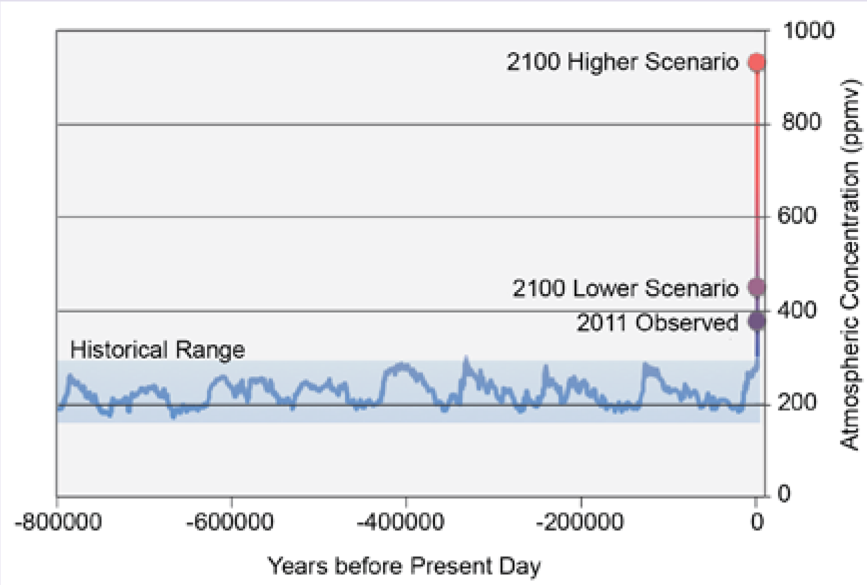


Figure 5. Air bubbles trapped in an Antarctic ice core extending back 800,000 years document the atmosphere's changing carbon dioxide concentration. Over long periods, natural factors have caused atmospheric CO_2 concentrations to vary between about 170 to 300 parts per million (ppm). As a result of human activities since the Industrial Revolution, CO_2 levels have increased to 400 ppm, higher than any time in at least the last one million years. By 2100, additional emissions from human activities are projected to increase CO_2 levels to 420 ppm under a very low scenario, which would require immediate and sharp emissions reductions (RCP 2.6), and 935 ppm under a higher scenario, which assumes continued increases in emissions (RCP 8.5). This figure shows the historical composite CO_2 record based on measurements from the EPICA (European Project for Ice Coring in Antarctica) Dome C and Dronning Maud Land sites and from the Vostok station. Data from Lüthi et al. 2008[9] (664-800 thousand years [kyr] ago, Dome C site); Siegenthaler et al. 2005[10] (393-664 kyr ago, Dronning Maud Land); Pépin 2001, Petit et al. 1999, and Raynaud 2005[11] (22-393 kyr ago, Vostok); Monnin et al. 2001[12] (0-22 kyr ago, Dome C); and Meinshausen et al. 2011[13] (future projections from RCP 2.6 and 8.5).

About 45% of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation. The remainder has built up in the atmosphere, where carbon dioxide levels have increased by about 40% relative to pre-industrial levels.

Methane levels in the atmosphere have increased due to human activities, including agriculture, with livestock producing methane in their digestive tracts, and rice farming producing it via bacteria that live in the flooded fields; mining coal, extraction and transport of natural gas, and other fossil fuel-related activities; and waste disposal including sewage and decomposing garbage in landfills. On average, about 55% to 65% of the emissions of atmospheric methane now come from human activities.[14,15] Atmospheric concentrations of methane leveled off from 1999-2006 due to temporary decreases in both human and natural sources,[14,15] but have been increasing again since then. Since preindustrial times, methane levels have increased by 250% to their current levels of 1.85 ppm.

Other greenhouse gases produced by human activities include ***nitrous oxide, halocarbons, and ozone.***

Nitrous oxide levels are increasing, primarily as a result of fertilizer use and fossil fuel burning. The concentration of nitrous oxide has increased by about 20% relative to pre-industrial times.

Halocarbons are manufactured chemicals produced to serve specific purposes, from aerosol spray propellants to refrigerant coolants. One type of halocarbon, long-lived chlorofluorocarbons (CFCs), was used extensively in refrigeration, air conditioning, and for various manufacturing purposes. However, in addition to being powerful heat-trapping gases, they are also responsible for depleting stratospheric ozone. Atmospheric levels of CFCs are now decreasing due to actions taken by countries under the Montreal Protocol, an international agreement designed to protect the ozone layer. As emissions and atmospheric levels of halocarbons continue to decrease, their effect on climate will also shrink. However, some of the replacement compounds are hydrofluorocarbons (HFCs), which are potent heat-trapping gases, and their concentrations are increasing.

Over 90% of the ozone in the atmosphere is in the stratosphere, where it protects the Earth from harmful levels of ultraviolet radiation from the sun. In the lower atmosphere, however, ozone is an air pollutant and also an important heat-trapping gas. Upper-atmosphere ozone levels have decreased because of human emissions of CFCs and other halocarbons. However, lower-atmosphere ozone levels have increased because of human activities, including transportation and manufacturing. These produce what are known as ozone precursors: air pollutants that react with sunlight and other chemicals to produce ozone. Since the late 1800s, average levels of ozone in the lower atmosphere have increased by more than 30%.[16] Much higher increases have been observed in areas with high levels of air pollution, and smaller increases in remote locations where the air has remained relatively clean.

Human activities can also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfur-containing particles reflect incoming sunlight away from the Earth, exerting a cooling influence on Earth's surface.

Another type of particle, composed mainly of soot, or black carbon, absorbs incoming sunlight and traps heat in the atmosphere, warming the Earth.

In addition to their direct effects, these particles can affect climate indirectly by changing the properties of clouds. Some encourage cloud formation because they are ideal surfaces on which water vapor can condense to form cloud droplets. Some can also increase the number, but decrease the average size of cloud droplets when there is not enough water vapor compared to the number of particles available, thus creating brighter clouds that reflect energy from the sun away from the Earth, resulting in an overall cooling effect. Particles that absorb energy encourage cloud droplets to evaporate by warming the atmosphere. Depending on their type, increasing amounts of particles can either offset or increase the warming caused by increasing levels of greenhouse gases. At the scale of the planet, the net effect of these particles is to offset between 20% and 35% of the warming caused by heat-trapping gases.

The effects of all of these greenhouse gases and particles on the Earth's climate depend in part on how long they remain in the atmosphere. Human-induced emissions of carbon dioxide have already altered atmospheric levels in ways that will persist for thousands of years. About one-third of the carbon dioxide emitted in any given year remains in the atmosphere 100 years later. However, the impact of past human emissions of carbon dioxide on the global carbon cycle will endure for tens of thousands of years. Methane lasts for approximately a decade before it is removed through chemical reactions. Particles, on the other hand, remain in the atmosphere for only a few days to several weeks. This means that the effects of any human actions to reduce particle emissions can show results nearly immediately. It may take decades, however, before the results of human actions to reduce long-lived greenhouse gas emissions can be observed. Some recent studies[17] examine various means for reducing near-term changes in climate, for example, by reducing emissions of short-lived gases like methane and particles like black carbon (soot). These approaches are being explored as ways to reduce the rate of short-term warming while more comprehensive approaches to reducing carbon dioxide emissions (and hence the rate of long-term warming) are being implemented.

In addition to emissions of greenhouse gases, air pollutants, and particles, human activities have also affected climate by changing the land surface. These changes include cutting and burning forests, replacing natural vegetation with agriculture or cities, and large-scale irrigation. These transformations of the land surface can alter how much heat is reflected or absorbed by the surface, causing local and even regional warming or cooling. Globally, the net effect of these changes has probably been a slight cooling influence over the past 100 years.

Considering all known natural and human drivers of climate since 1750, a strong net warming from long-lived greenhouse gases produced by human activities dominates the recent climate record. This warming has been partially offset by increases in atmospheric particles and their effects on clouds. Two important natural external drivers also influence climate: the sun and volcanic eruptions. Since 1750, these natural external drivers are estimated to have had a small net warming influence, one that is much smaller than the human influence. Natural internal climate variations, such as El Niño events in

Relative Strengths of Warming and Cooling Influences

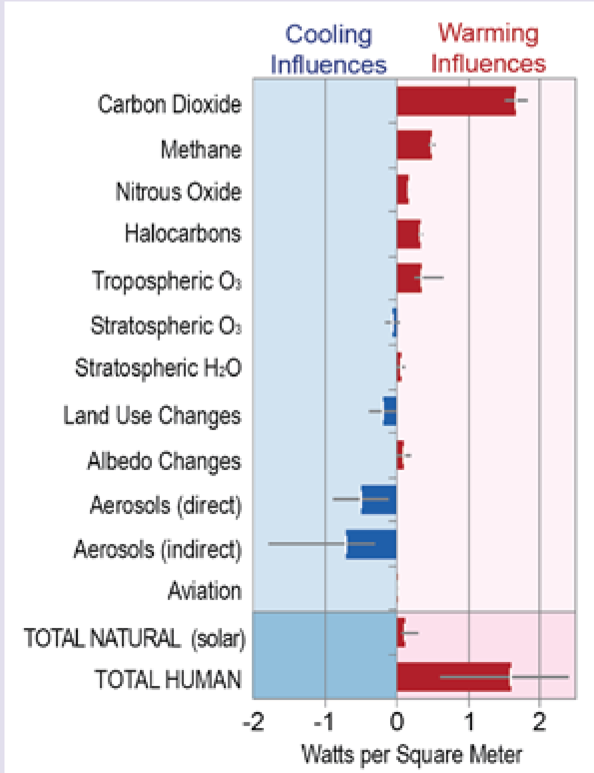


Figure 6. Different factors have exerted a warming influence (red bars) or a cooling influence (blue bars) on the planet. The warming or cooling influence of each factor is measured in terms of the change in radiative forcing in watts per square meter by 2005 relative to 1750. This figure includes all the major human-induced factors as well as the sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural, but is relatively short-lived and so is not included here. Aerosols refer to tiny particles, with their direct effects including, for example, the warming influence of black carbon (soot) and cooling influence of sulfate particles from coal burning. Indirect effects of aerosols include their effect on clouds. The net radiative influence from natural and human influences is a strong warming, predominantly from human activities. The thin lines on each bar show the range of uncertainty. (Figure source: adapted from *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Figure 2.20 (A), Cambridge University Press[15]).

the Pacific Ocean, have also influenced regional and global climate. Several other modes of internal natural variability have been identified, and their effects on climate are superimposed on the effects of human activities, the sun, and volcanoes.

During the last three decades, direct observations indicate that the sun's energy output has decreased slightly. The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting two to three years. Thus, natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has been a slight cooling influence over this period. In addition, the changes occurring now are very rapid compared to the major changes in climate over at least the last several thousand years.

It is not only the direct effects from human emissions that affect climate. These direct effects also trigger a cascading set of feedbacks that cause indirect effects on climate – acting to increase or dampen an initial change. For example, water vapor is the single most important gas responsible for the natural greenhouse effect. Together, water vapor and clouds account for between 66% and 80% of the natural greenhouse effect.[18] However, the amount of water vapor in the atmosphere depends on temperature; increasing temperatures increase the amount of water vapor. This means that the response of water vapor is an internal feedback, not an external forcing of the climate.

Observational evidence shows that, of all the external forcings, an increase in atmospheric CO_2 concentration is the most important factor in increasing the heat-trapping capacity of the atmosphere. Carbon dioxide and other gases, such as methane and nitrous oxide, do not condense and fall out of the atmosphere, whereas water vapor does (for example, as rain or snow). Together, heat-trapping gases other than water vapor account for between 26% and 33% of the total greenhouse effect,[18] but are responsible for most of the changes in climate over recent decades. This is a range, rather than a single number, because some of the absorption effects of water vapor overlap with those of the other important gases. Without the heat-trapping effects of carbon dioxide and the other non-water vapor greenhouse gases, climate simulations indicate that the greenhouse effect would not function, turning the Earth into a frozen ball of ice.[19]

The average conditions and the variability of the Earth's climate are critical to all aspects of human and natural systems on the planet. Human society has become increasingly complex and dependent upon the climate system and its behavior. National and global infrastructures, economies, agriculture, and ecosystems are adapted to the present climate state, which from a geologic timescale perspective has been remarkably stable for the past several thousand years. Any significant perturbation, in either direction, would have substantial impacts upon both human society and the natural world. The magnitude of the human influence on climate and the rate of change raise concerns about the ability of ecosystems and human systems to successfully adapt to future changes.

Supplemental Message 2.

Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.

There are many types of observations that can be used to detect changes in climate and determine what is causing these changes. Thermometer and other instrument-based surface weather records date back hundreds of years in some locations. Air temperatures are measured at fixed locations over land and with a mix of predominantly ship- and buoy-based measurements over the ocean. By 1850, a sufficiently extensive array of land-based observing stations and ship-borne observations had accumulated to begin tracking global average temperature. Measurements from weather balloons began in the early 1900s, and by 1958 were regularly taken around the world. Satellite records beginning in the 1970s provide additional perspectives, particularly for remote areas such as the Arctic that have limited ground-based observations. Satellites also provided new capabilities for mapping precipitation and upper air temperatures. Climate "proxies" – biological or physical records ranging from tree rings to ice cores that correlate with aspects of climate – provide further evidence of past climate that can stretch back hundreds of thousands of years.

These diverse datasets have been analyzed by scientists and engineers from research teams around the world in many different ways. The most high-profile indication of the changing climate is the surface temperature record, so it has received the most attention. Spatial coverage, equipment, methods of observation, and many other aspects of the measurement record have changed over time, so scientists identify and adjust for these changes. Independent research groups have looked at the surface temperature record for land[21] and ocean[22] as well as land and ocean combined.[23,24] Each group takes a different approach, yet all agree that it is unequivocal that the planet is warming.

There has been widespread warming over the past century. Not every region has warmed at the same pace, however, Development of Observing Capabilities

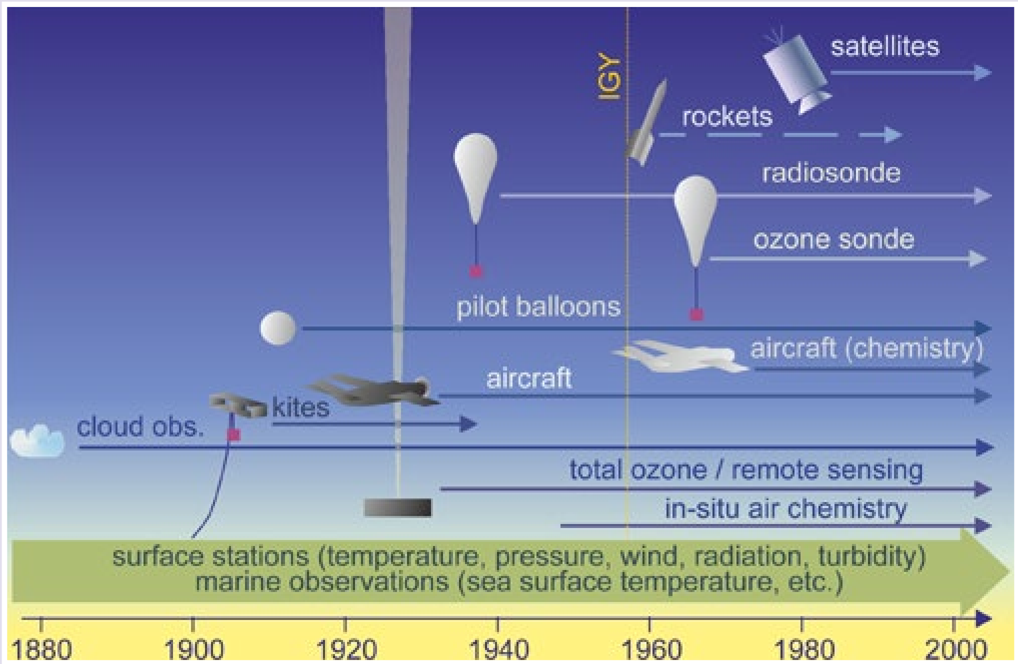


Figure 7. Changes in the mix and increasing diversity of technologies used to observe climate (IGY is the International Geophysical Year). (Figure source: adapted from Brönnimann et al. 2007[20]).

and a few regions, such as the North Atlantic Ocean (Figure 9) and some parts of the U.S. Southeast (Ch. 2: Our Changing Climate, Figure 2.7), have even experienced cooling over the last century as a whole, though they have warmed over recent decades. This is due to the stronger influence of internal variability over smaller geographic regions and shorter time scales, as mentioned in Supplemental Message 1 and discussed in more detail in Supplemental Message 3. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming in response to accelerating increases in heat-trapping gas concentrations, particularly at high northern latitudes, and over land as compared to ocean.

Observed Change in Global Average Temperature

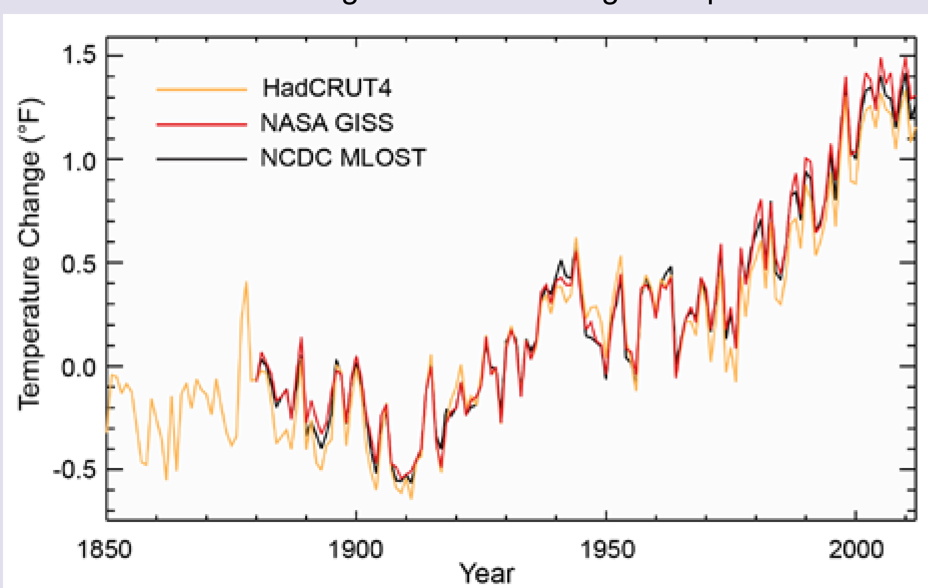


Figure 8. Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

Temperature Trends: Past Century, Past 30+ Years

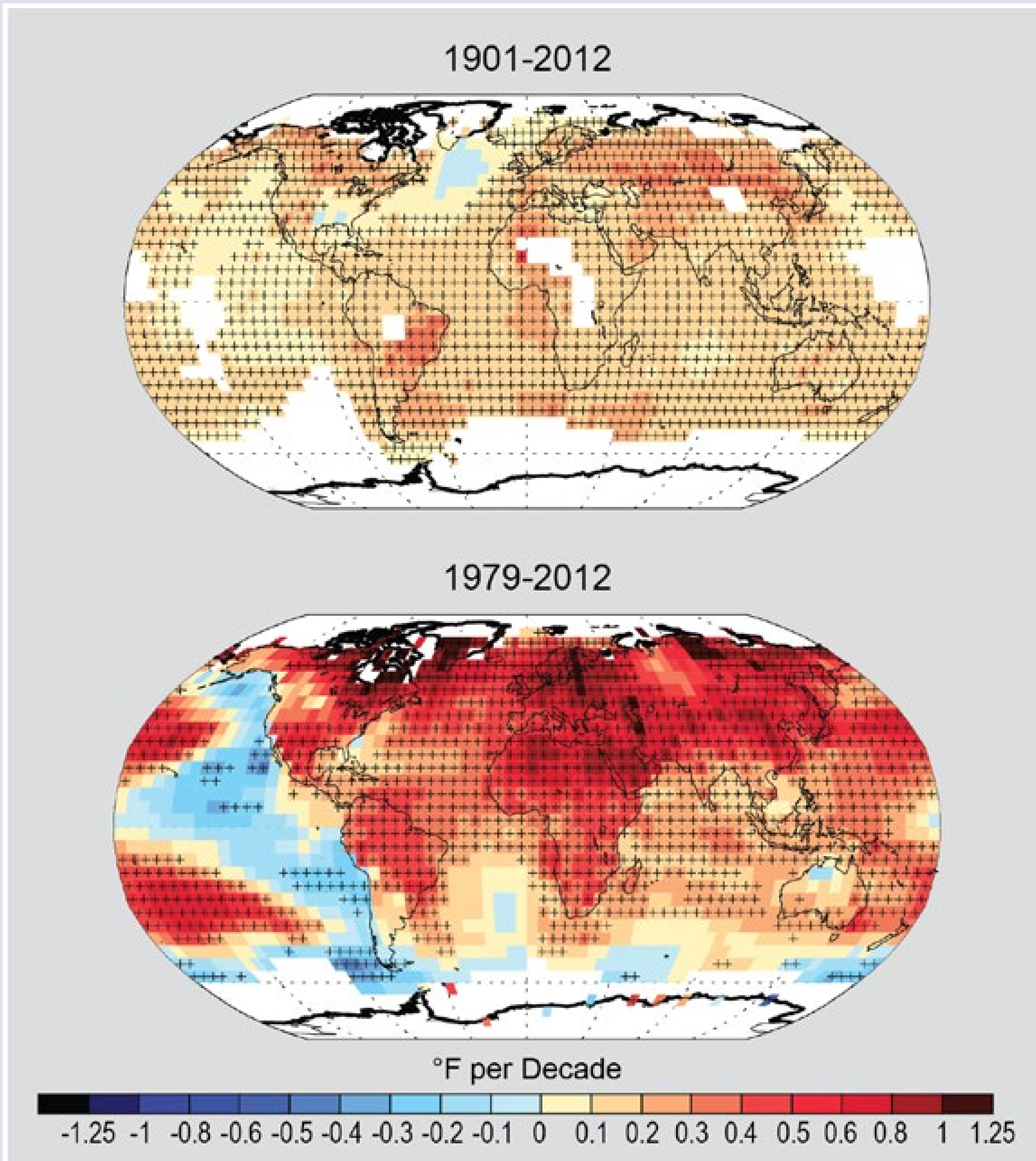


Figure 9. Surface temperature trends for the period 1901-2012 (top) and 1979-2012 (bottom) from the National Climatic Data Center's (NCDC) surface temperature product. The relatively coarse resolution of these maps does not capture the finer details associated with mountains, coastlines, and other small-scale effects. (Figure source: updated from Vose et al. 2012[24]).

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been increasing because multiple lines of evidence all support this conclusion. Temperatures in the lower atmosphere and oceans have increased, as have sea level and near-surface humidity. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. As with temperature, multiple research groups have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming world.

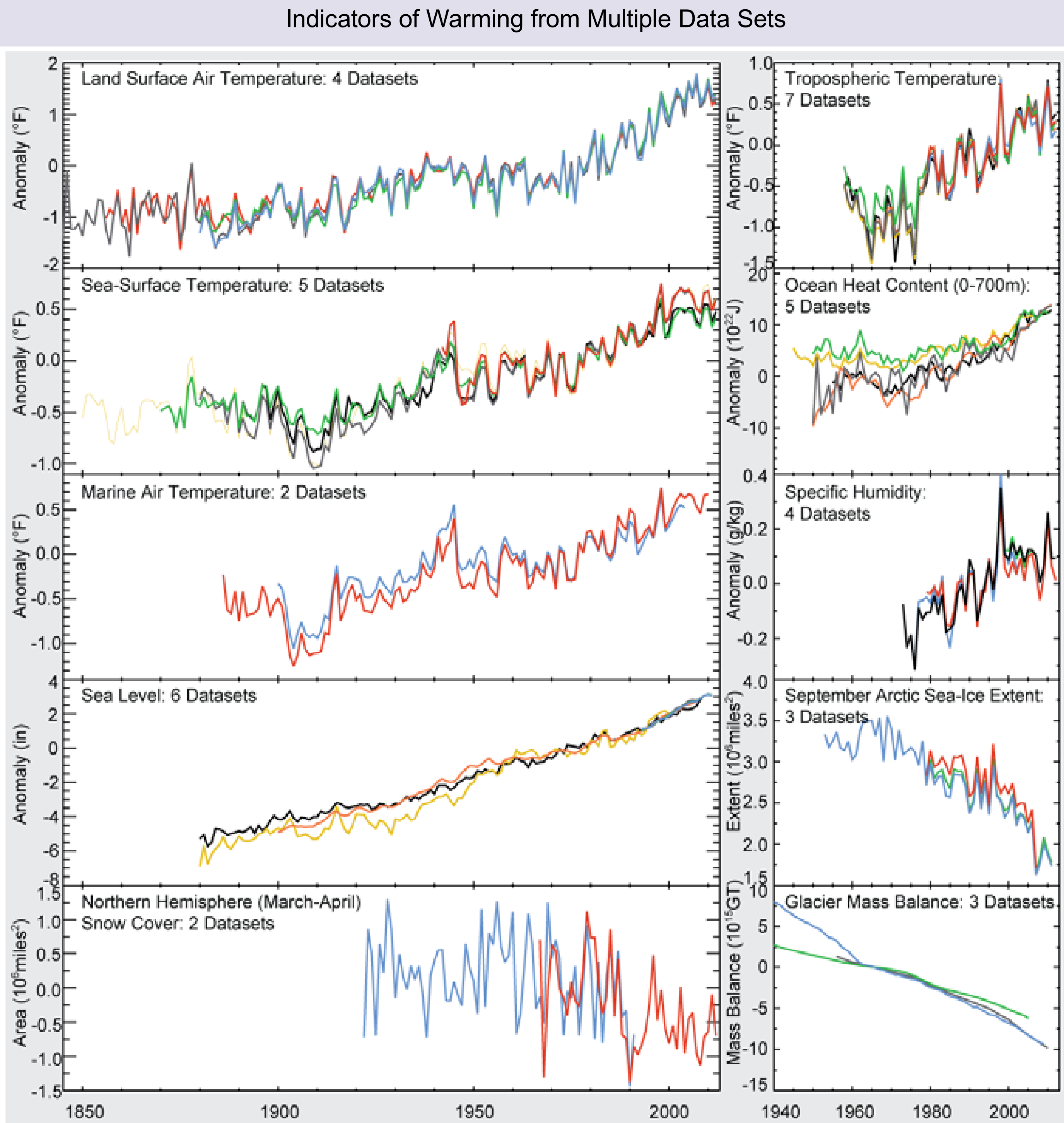


Figure 10. Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing as expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. (Figure source: updated from Kennedy et al. 2010[25]).

Not all of the observed changes are directly related to temperature; some are related to the hydrological cycle (the way water moves cyclically among land, ocean, and atmosphere). Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for over a century. However, spatial scales of precipitation are small (it can rain several inches in Washington, D.C., but not a drop in Baltimore) and this makes interpretation of the point-measurements difficult. Based upon a range of efforts to create global averages, it is likely that there has been little change in globally averaged precipitation since 1900. However, there are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude regions taken as a whole. In general, wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to global warming.

Analyses of past changes in climate during the period before instrumental records (referred to as paleoclimate) allow current changes in atmospheric composition, sea level, and climate (including extreme events), as well as future projections, to be placed in a broader perspective of past climate variability. A number of different reconstructions of the last 1,000 to 2,000 years[26,27] give a consistent picture of Northern Hemisphere temperatures, and in a few cases, global temperatures, over that time period. The analyses in the Northern Hemisphere indicate that the 1981 to 2010 period (including the last decade) was the warmest of at least the last 1,300 years and probably much longer.[28,29] A reconstruction going back 11,300 years ago[30] suggests that the last decade was warmer than at least 72% of global temperatures since the end of the last ice age 20,000 years ago. The observed warming of the last century has also apparently reversed a long-term cooling trend at mid- to high latitudes of the Northern Hemisphere throughout the last 2,000 years.

Other analyses of past climates going back millions of years indicate that past periods with high levels (400 ppm or greater) of CO_2 were associated with temperatures much higher than today's and with much higher sea levels.[31]

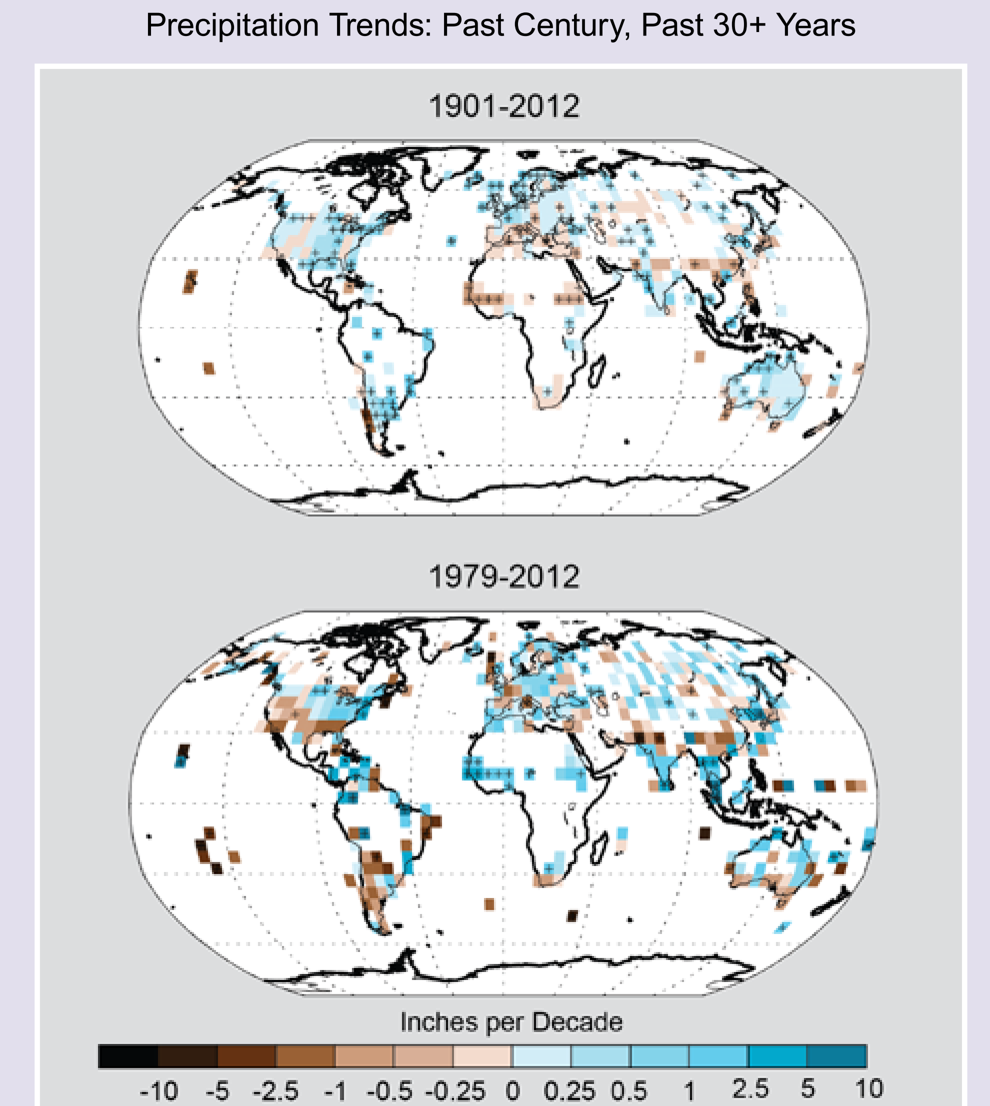


Figure 11. Global precipitation trends for the period 1901-2012 (top) and 1979-2012 (bottom). (Figure source: NOAA NCDC / CICS-NC).

1700 Years of Global Temperature Change from Proxy Data

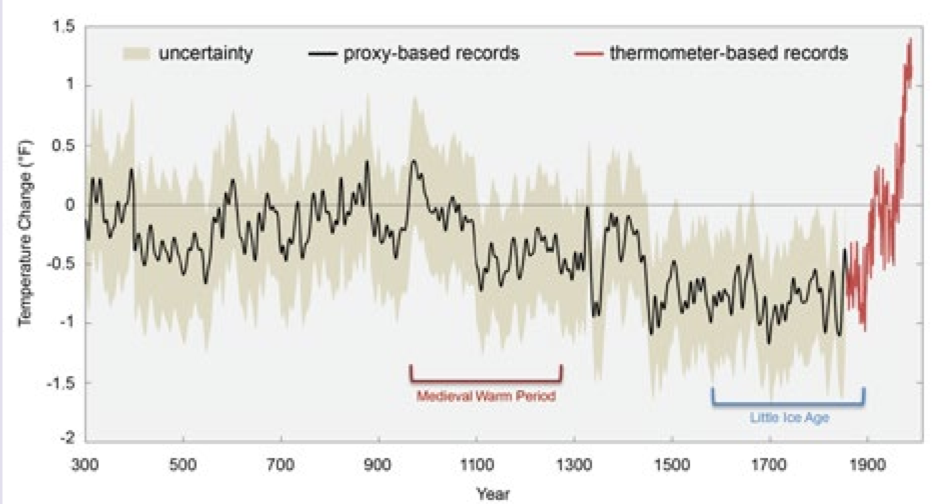


Figure 12. Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years, and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[27]).

Supplemental Message 3.

Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.

Natural variations internal to the Earth's climate system can drive increases or decreases in global and regional temperatures, as well as affect precipitation and drought patterns around the world. Today, average temperature, precipitation, and other aspects of climate are determined by a combination of human-induced changes superimposed on natural variations in both internal and external factors such as the sun and volcanoes (see Supplemental Message 1). The relative magnitudes of the human and natural contributions to temperature and climate depend on both the time and spatial scales considered. The magnitude of the effect humans are having on global temperature specifically, and on climate in general, has been steadily increasing since the Industrial Revolution. At the global scale, the human influence on climate can be either masked or augmented by natural internal variations over timescales of a decade or so (for example, Tung and Zhou 2013[32]). At regional and local scales, natural variations have an even larger effect. Over longer periods of time, however, the influence of internal natural variability on the Earth's climate system is negligible; in other words, over periods longer than several decades, the net effect of natural variability tends to sum to zero.

There are many modes of natural variability within the climate system. Most of them involve cyclical exchanges of heat and energy between the ocean and atmosphere. They are manifested by recurring changes in sea surface temperatures, for example, or by surface pressure changes in the atmosphere. While many global climate models are able to simulate the spatial patterns of ocean and atmospheric variability associated with these modes, they are less able to capture the chaotic variability in the timescales of the different modes.[33]

The largest and most well-known mode of internal natural variability is the El Niño/Southern Oscillation or ENSO. This natural mode of variability was first identified as a warm current of ocean water off the coast of Peru, accompanied by a shift in pressure between two locations on either side of the Pacific Ocean. Although centered in the tropical Pacific, ENSO affects regional temperatures and precipitation around the world by heating or cooling the lower atmosphere in low latitudes, thereby altering pressure gradients aloft. These pressure gradients, in turn, drive the upper-level winds and the jet stream that dictates patterns of mid-latitude weather, as shown in Figure 13. In the United States, for example, the warm ENSO phase (commonly referred to as El Niño) is usually associated with heavy rainfall and flooding in California and the Southwest, but decreased precipitation in the Northwest.[34] El Niño conditions also tend to suppress Atlantic hurricane formation by increasing the amount of wind shear in the region where hurricanes form.[35] The cool ENSO phase (usually called

La Niña and El Niño Patterns

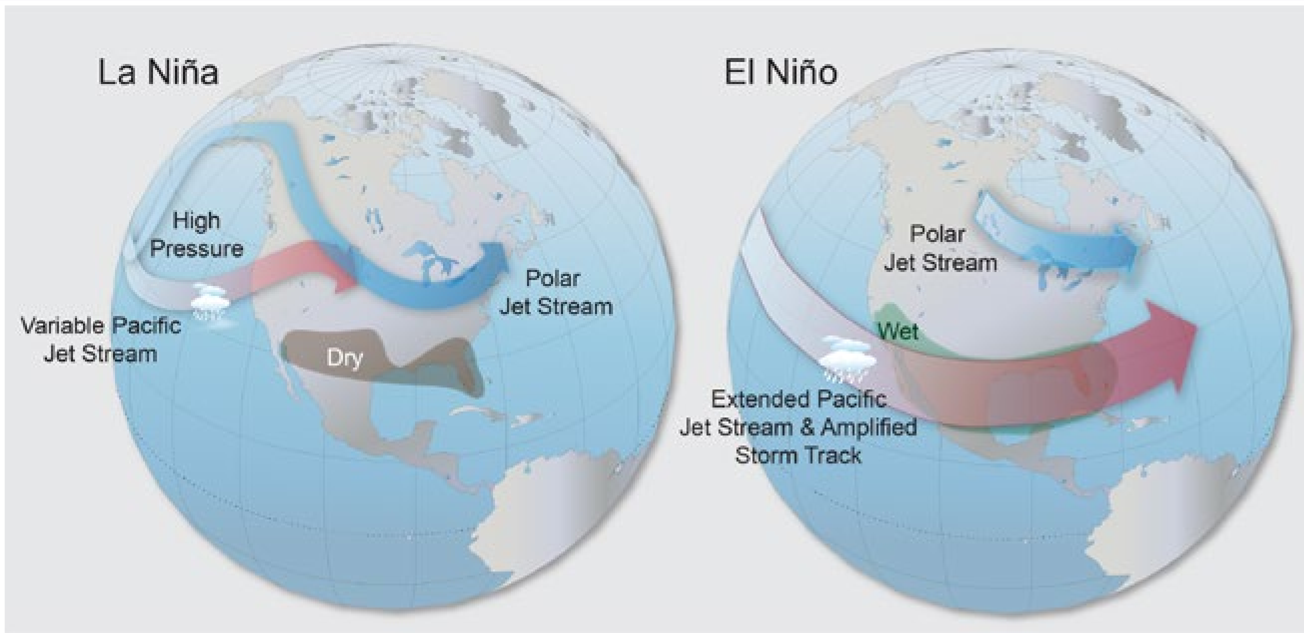


Figure 13. Typical January-March weather conditions and atmospheric circulation (jet streams shown by red and blue arrows) during La Niña and El Niño conditions. Cloud symbols show areas that are wetter than normal. During La Niña, winters tend to be unusually cold in eastern Alaska and western Canada, and dry throughout the southern United States. El Niño leads to unusually warm winter conditions in the northern U.S. and wetter than average conditions across the southern U.S. (Figure source: NOAA).

Warming Trend and Effects of El Niño/La Niña
GISTEMP Land-Ocean Index

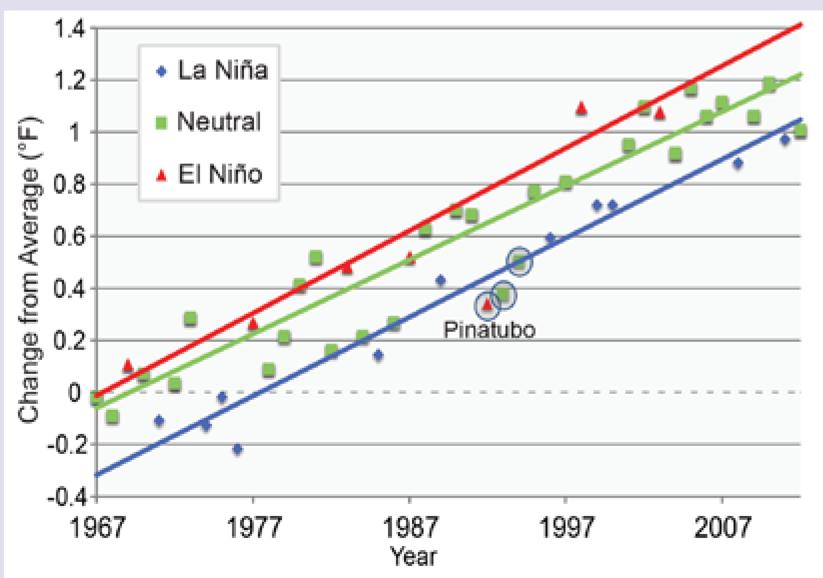


Figure 14. Trends in globally and annually averaged temperature when considering whether it was an El Niño year, a La Niña year, or a neutral year (no El Niño or La Niña event). The average global temperature is 0.4ºF higher in El Niño years than in La Niña years. However, all trends show the same significant increase in temperature over the past 45 years. The years for the short-term cooling effect following the Mt. Pinatubo volcanic eruption are not included in the trends. (Figure source: adapted from John Nielsen-Gammon 2012.[38] Data from NASA GISS temperature dataset[39] and Climate Prediction Center Niño 3.4 index[40]).

La Niña) is associated with dry conditions in the Central Plains,[36] as well as a more active Atlantic hurricane season. Although these and other conditions are typically associated with ENSO, no two ENSO events are exactly alike.

Natural modes of variability such as ENSO can also affect global temperatures. In general, El Niño years tend to be warmer than average and La Niña years, cooler. The strongest El Niño event recorded over the last hundred years occurred in 1998. Superimposed on the long-term increase in global temperatures due to human activities, this event caused record high global temperatures. After 1998, the El Niño event subsided, resulting in a slowdown in the temperature increase since 1998. Overall, however, years in which there are El Niño, La Niña, or neutral conditions all show similar long-term warming trends in global temperature (see Figure 14).

Natural modes of variability like ENSO are not necessarily stationary. For example, there appears to have been a shift in the pattern and timing of ENSO in the mid-1970s, with the location of the warm water pool shifting from the eastern to the central Pacific and the frequency of events increasing. Paleoclimate studies using tree rings show that ENSO activity over the last 100 years has been the highest in the last 500 years,[37] and both paleoclimate and modeling studies suggest that global temperature increases may interact with natural variability in ways that are difficult to predict. Climate models can simulate the statistical behavior of these variations in temperature trends. For example, models can project whether some phenomena will increase or decrease in frequency, but cannot predict the exact timing of particular events far into the future.

There are other natural modes of variability in the climate system. For example, the North Atlantic Oscillation is frequently linked to variations in winter snowfall along the Atlantic seaboard. The Pacific Decadal Oscillation was first identified as a result of its effect on the Pacific salmon harvest. The influence of these and other natural variations on global temperatures is generally less than ENSO, but local influences may be large.

A combination of natural and human factors explains regional "warming holes" where temperatures actually decreased for several decades in the middle to late part of the last century at a few locations around the world. In the United States, for example, the Southeast and parts of the Great Plains and Midwest regions did not show much warming over that time period, though they have warmed in recent decades. Explanations include increased cloud cover and precipitation,[41] increased small particles from coal burning, natural factors related to forest re-growth,[42] decreased heat flux due to irrigation,[43] and multi-decade variability in North Atlantic and tropical Pacific sea surface temperatures.[44,45] The importance of tropical Pacific and Atlantic sea surface temperatures on temperature and precipitation variability over the central U.S. has been particularly highlighted by many studies. Over the next few decades, as the multi-decadal tropical Pacific Ocean cycle continues its effect on sea surface temperatures, the U.S. Southeast could warm at a rate that is faster than the global average.[45]

At the global scale, natural variability will continue to modify the long-term trend in global temperature due to human activities, resulting in greater and lesser trends over relatively short time scales. Interactions among various components of the Earth's climate system produce patterns of natural variability that can be chaotic, meaning that they are sensitive to the initial conditions of the climate system. Global climate models simulate natural variability with varying degrees of realism, but the timing of these random variations differs among models and cannot be expected to coincide with those of the actual climate system. Over climatological time periods, however, the net effect of natural internal variability on the global climate

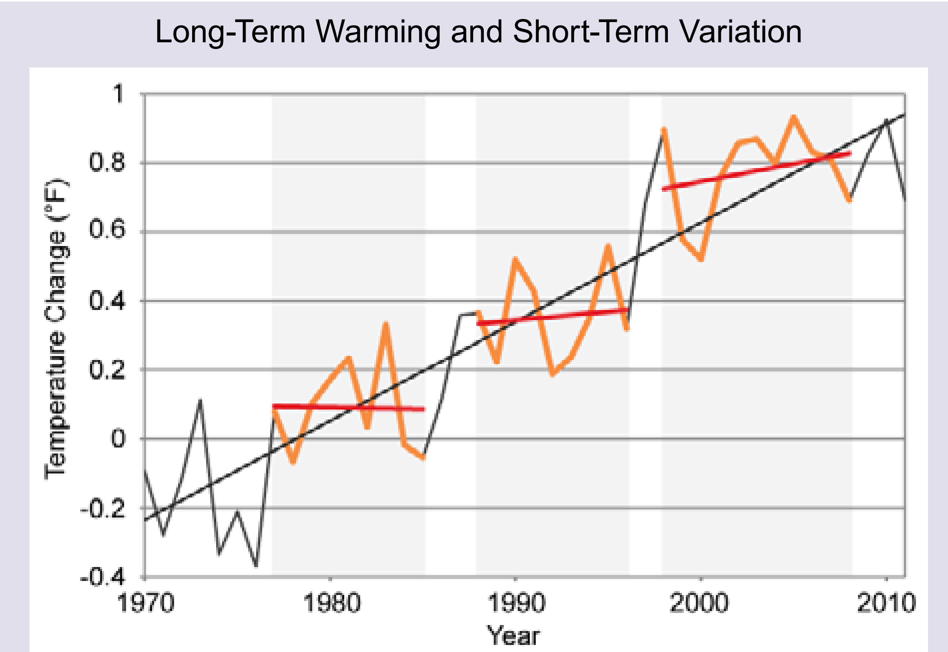


Figure 15. Observations of global mean surface air temperature show that although there can be short periods with little or even no significant upward trend (red trend lines in shaded areas), global temperature continues to rise unabated over long-term climate timescales (black trend line). The recent period, 1998-2012, is another example of a short-term pause embedded in the underlying warming trend. The differences between short-term trends and the underlying (long-term) trend are often associated with modes of natural variability such as El Niño and La Niña that redistribute heat between the ocean and atmosphere. (Data from NOAA NCDC).

tends to average to zero. For example, there can be warmer years due to El Niño (such as 1998) and cooler years due to La Niña (such as 2011), but over multiple decades the net effect of natural variability on uncertainty in global temperature and precipitation projections is small.

Averaging (or compositing) of projections from different models smooths out the randomly occurring natural variations in the different models, leaving a clear signal of the long-term externally forced changes in climate, not weather. In this report, all future projections are averaged over 20- to 30-year time periods.

Supplemental Message 4.

Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.

Determining the causes of climate changes is a field of research known as "detection and attribution." *Detection* involves identifying a climate trend or event (for instance, long-term surface air temperature trends, or a particularly extreme heat wave) that is strikingly outside the norm of natural variations in the climate system. Similar to conducting forensic analysis on evidence from a crime scene, *attribution* involves considering the possible causes of an observed event or change, and identifying which factor(s) are responsible.

Detection and attribution studies use statistical analyses to identify the causes of observed changes in temperature, precipitation, and other aspects of climate. They do this by trying to match the complex "fingerprint" of the observed climate system behavior to a set of simulated changes in climate that would be caused by different forcings.[46] Most approaches consider not only global but also regional patterns of changes over time.

Climate simulations are used to test hypotheses regarding the causes of observed changes. First, simulations that include changes in both natural and human forcings that may cause climate changes, such as changes in energy from the sun and increases in heat-trapping gases, are used to characterize what

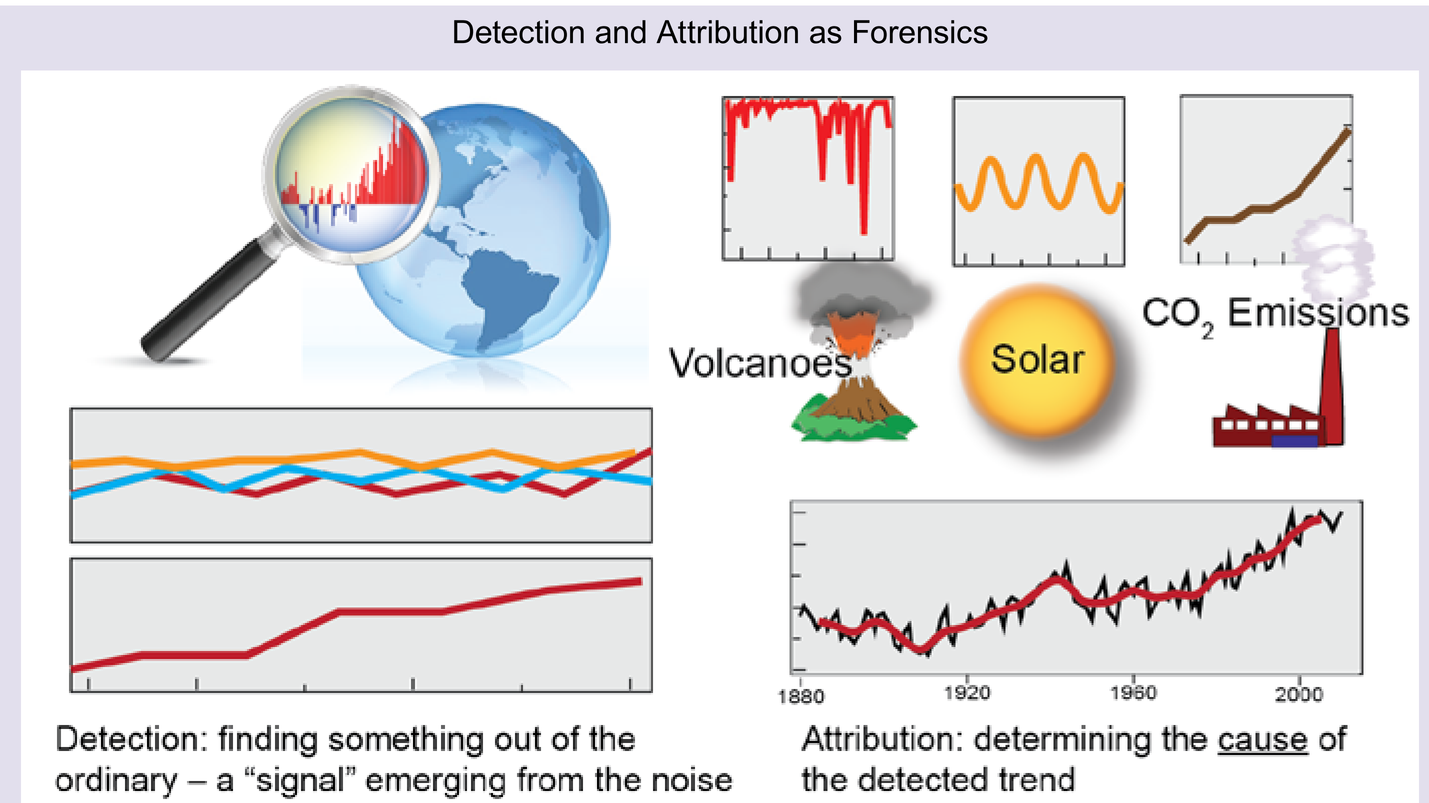


Figure 16. Simplified image of the methodology that goes into detection and attribution of climate changes. The natural factors considered usually include changes in the sun's output and volcanic eruptions, as well as natural modes of variability such as El Niño and La Niña. Human factors include the emissions of heat-trapping gases and particles as well as clearing of forests and other land-use changes. (Figure source: NOAA NCDC / CICS-NC).

Human Influences Apparent in Many Aspects of the Changing Climate

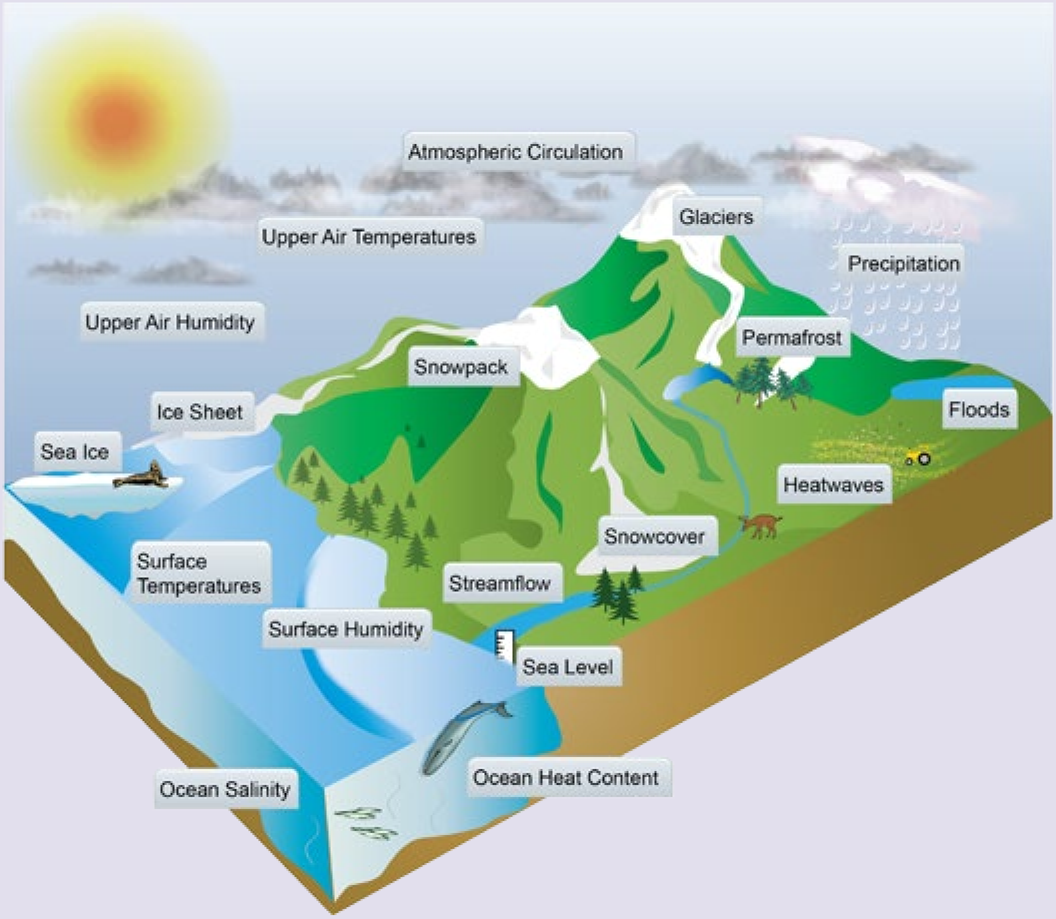


Figure 17. Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

effect those factors would have had working together. Then, simulations with no changes in external forcings, only changes due to natural variability, are used to characterize what would be expected from normal internal variations in the climate. The results of these simulations are compared to observations to see which provides the best match for what has really occurred.

Detection and attribution studies have been applied to study a broad range of changes in the climate system as well as a number of specific extreme events that have occurred in recent years. These studies have found that human influences are the only explanation for the observed changes in climate over the last half-century. Such changes include increases in surface temperatures,[46,47] changes in atmospheric vertical temperature profiles,[48] increases in ocean heat content,[49] increasing atmospheric humidity,[50] increases in intensity of precipitation[51] and in runoff,[52] indirectly estimated through changes in ocean salinity,[53] shifts in atmospheric circulation,[54] and changes in a host of other indices.[46] Taken together these paint a coherent picture of a planet whose climate is changing primarily as a result of human activities.

Detection and attribution of specific events is more challenging than for long-term trends as there are less data, or evidence, available from which to draw conclusions. Attribution of extreme events is especially scientifically challenging.[56] Many extreme weather and climate events observed to date are within the range of what could have occurred naturally, but the probability, or odds, of some of these very rare events occurring[57] has been significantly altered by human influences on the climate system. For example, studies have concluded that there is a detectable human influence in recent heat waves in Europe,[58] Russia,[59] and Texas[60] as well as flooding events in England and Wales,[61] the timing and magnitude of snowmelt and resulting streamflow in some western U.S. states,[62,63] and some specific events around the globe during 2011.[64]

Only Human Influence Can Explain Recent Warming

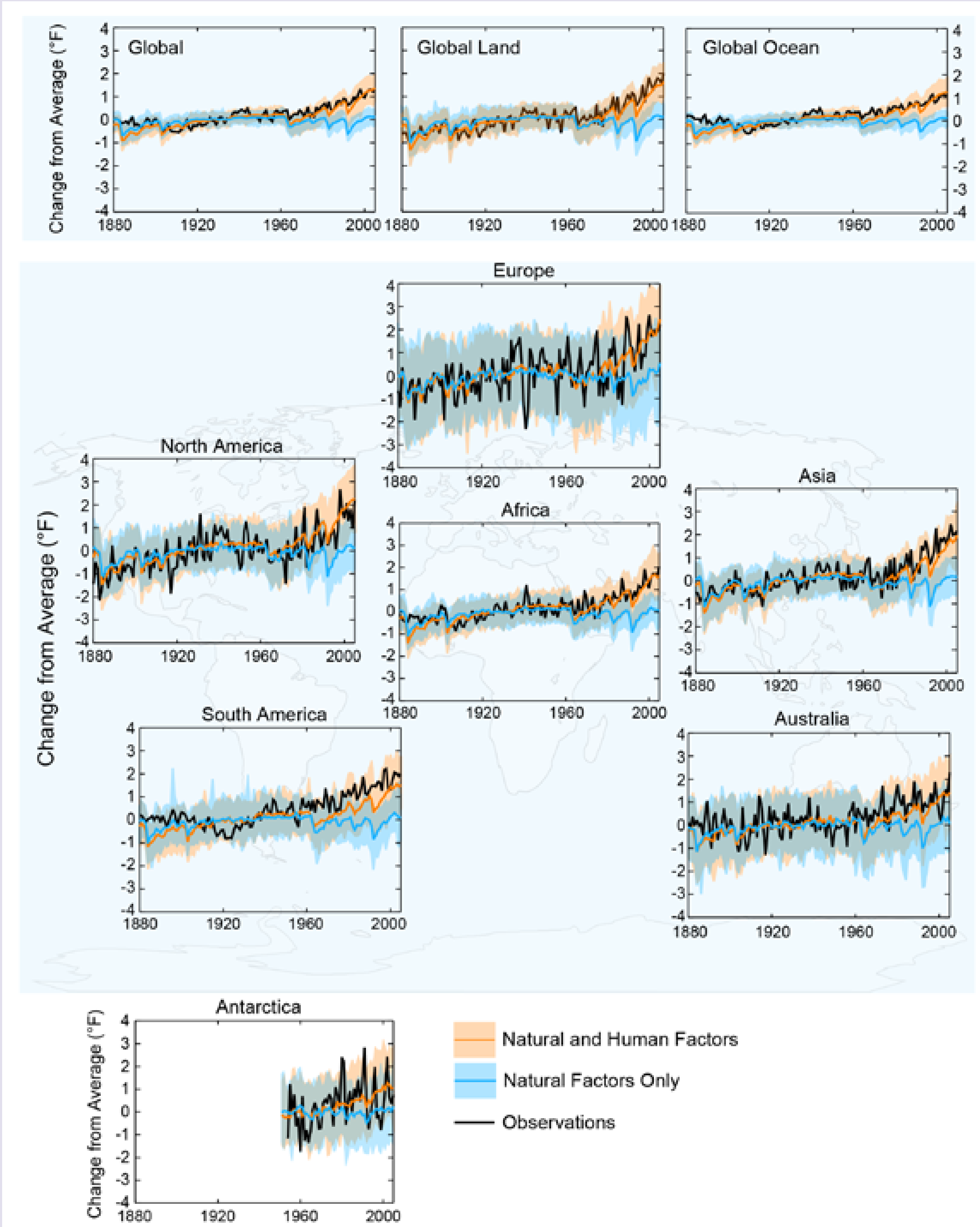


Figure 18. Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading shows climate model simulations that include the effects of natural (solar and volcanic) forcing only. The orange shading shows climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013[55]).

Supplemental Message 5.

Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.

A certain amount of climate change is already inevitable due to the build-up of CO_2 in the atmosphere from human activities, most of it since the Industrial Revolution. A decrease in temperature would only be expected if there was an unexpected decrease in natural forcings, such as a reduction in the power of the sun. The Earth's climate system, particularly the ocean, tends to lag behind changes in atmospheric composition by decades, and even centuries, due to the large heat capacity of the oceans and other factors. Even if all emissions of the relevant gases and particles from human activity suddenly stopped, a temperature increase of 0.5°F still would occur over the next few decades,[65] and the human-induced changes in the global carbon cycle would persist for thousands of years.[66]

Global emissions of CO_2 and other heat-trapping gases continue to rise. How much climate will change over this century and beyond depends primarily on: 1) human activities and resulting emissions, and 2) how sensitive the climate is to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions). Uncertainties in how the economy will evolve, what types of energy will be used, or what our cities, buildings, or cars will look like in the future all limit scientists' ability to predict the future changes in climate. Scientists can, however, develop scenarios – plausible projections of what might happen, under a given set of assumptions. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

Over the next few decades, the greater part of the range (or uncertainty) in projected global and regional change is the result of natural variability and scientific limitations in our ability to model and understand the Earth's climate system (natural variability is discussed in Supplemental Message 3 and scientific or model uncertainty in Supplemental Message 6). By the second half of the century, however, scenario uncertainty (that is, uncertainty about what will be the level of emissions from human activities) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects.[67] Even though natural variability will continue to occur, most of the difference between present and future climates will be determined by choices that society makes today and over the next few decades. The further out in time we look, the greater the influence of human choices on the magnitude of future change.

For temperature, it is clear that increasing emissions from human activities will drive consistent increases in global and most regional temperatures and that these rising temperatures will increase with the magnitude of future emissions (see Figure 19 and Ch. 2: Our Changing Climate, Figures 2.8 and 2.9). Uncertainty in projected temperature change is generally smaller than uncertainty in projected changes in precipitation or other aspects of climate.

Future climate change also depends on "climate sensitivity," generally summarized as the response of global temperature to a doubling of CO_2 levels in the atmosphere relative to preindustrial levels of 280 parts per million. If the only impact of increasing atmospheric CO_2 levels were to amplify the natural greenhouse effect (as CO_2 levels increase, more of the Earth's heat is absorbed by the atmosphere before it can escape to space, as discussed in Supplemental Message 1), it would be relatively easy to calculate the change in global temperature that would result from a given increase in CO_2 levels. However, a series of feedbacks within the Earth's climate system acts to amplify or diminish an initial change, adding some uncertainty to the precise climate sensitivity. Some important feedbacks include:

- Clouds – Will warming increase or decrease cloudiness? Will the changes be to lower-altitude clouds that primarily reflect the sun's energy, or higher clouds that trap even more heat within the Earth system?

- Albedo (reflectivity) – How quickly will bright white reflective surfaces, such as snow and ice that reflect most of the sun's energy, melt and be replaced by a dark ocean or land area that absorbs most of the sun's energy? How will vegetation changes caused by climate change alter surface reflectivity?

- Carbon dioxide absorption by the ocean and the biosphere – Will the rate of uptake increase in the future, helping to remove human emissions from the atmosphere? Or will it decrease, causing emissions to build up even faster than they are now?

Feedbacks are particularly important in the Arctic, where rising temperatures melt ice and snow, exposing relatively dark land and ocean, which absorb more of the sun's energy, heating the region even further. Rising temperatures also thaw permafrost, releasing carbon dioxide and methane trapped in the previously frozen ground into the atmosphere, where they further amplify the greenhouse effect (see Supplemental Message 1). Both of these feedbacks act to further amplify the initial warming due to human emissions of carbon dioxide and other heat-trapping gases.

Together, these and other feedbacks determine the long-term response of the Earth's temperature to an increase in carbon dioxide and other emissions from human activities. Past observations, including both recent measurements and studies that look at climate changes in the distant past, cannot tell us precisely how sensitive the climate system will be to increasing emissions of heat-trapping gases if we are starting from today's conditions. They can tell us, however, that the net effect of these feedbacks will be to increase, not diminish, the direct warming effect. In other words, the climate system will warm by more than would be expected from the greenhouse effect alone.

Quantifying the effect of these feedbacks on global and regional climate is the subject of ongoing data collection and active research. As noted above, one measure used to study these effects is the "equilibrium climate sensitivity," which is an estimate of the temperature change that would result, once the climate had reached an equilibrium state, as a result of doubling the CO_2 concentration from pre-industrial levels. The equilibrium climate sensitivity has long been estimated to be in the range of 2.7°F to 8.1°F. The 2007 IPCC Fourth Assessment Report[15] refined this range based on more recent evidence to conclude that the value is likely to be in the range 3.6°F to 8.1°F, with a most probable value of about 5.4°F, based upon multiple observational and modeling constraints, and that it is very unlikely to be less than 2.7°F. Climate sensitivities determined from a variety of evidence agree well with this range, including analyses of past paleoclimate changes.[68,69] This is substantially greater than the increase in temperature from just the direct radiative effects of the CO_2 increase (around 2°F).

Some recent studies (such as Fasullo and Trenberth 2012[70]) have suggested that climate sensitivities are at the higher end of this range, while others have suggested values at the lower end of the range.[71,72] Some recent studies have even suggested that the climate sensitivity may be less than 2.7°F based on analyses of recent temperature trends.[72] However, analyses based on recent temperature trends are subject to significant uncertainties in the treatment of natural variability,[69] the effects of volcanic eruptions,[73] and the effects of recent accelerated penetration of heat to the deep ocean.[74]

The equilibrium climate sensitivity is sometimes confused with the "transient climate response," defined as the temperature change for a 1% per year CO_2 increase, and calculated using the difference between the start of the experiment and a 20-year period centered on the time of CO_2 doubling. This value is generally smaller than the equilibrium climate sensitivity because of the slow rate at which heat transfers between the oceans and the atmosphere due to transient heat uptake of the ocean. The transient climate response is better constrained than the equilibrium climate sensitivity.[15] It is very likely larger than 1.8°F and very unlikely to be greater than 5.4°F. This transient response includes feedbacks that respond to global temperature change over timescales of years to decades. These "fast" feedbacks include increases in atmospheric water vapor, reduction of ice and snow, warming of the ocean surface, and changes in cloud characteristics. The entire response of the climate system will not be fully seen until the deep ocean comes into balance with the atmosphere, a process that can take thousands of years.

Combining the uncertainty due to climate sensitivity with the uncertainty due to human activities produces a range of future temperature changes that overlap over the first half of this century, but begins to separate over the second half of the century as emissions and atmospheric CO_2 levels diverge.

Emissions, Concentrations, and Temperature Projections

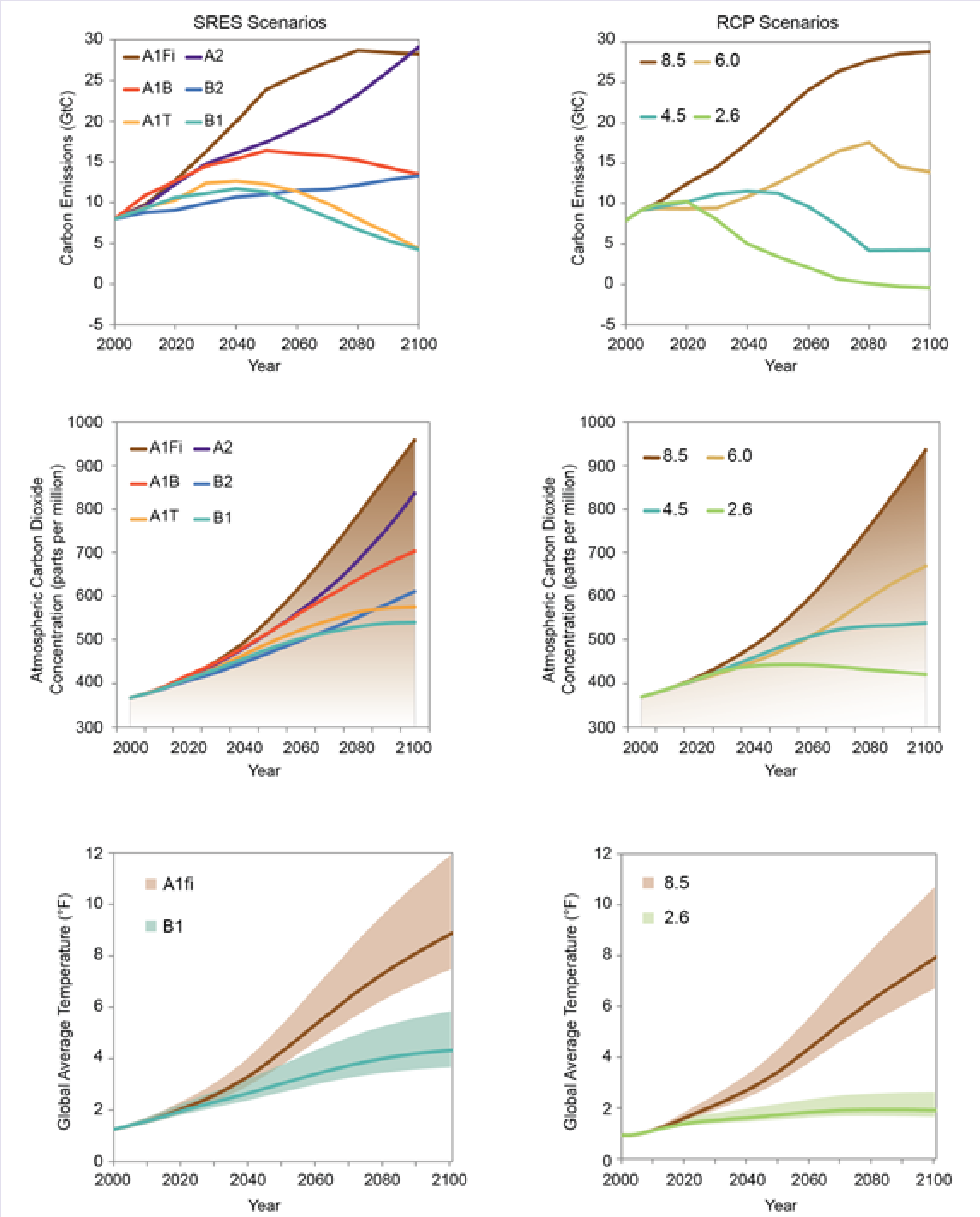


Figure 19. Two families of scenarios are commonly used for future climate projections: the 2000 Special Report on Emission Scenarios (SRES, left) and the 2010 Representative Concentration Pathways (RCP, right). The SRES scenarios are named by family (A1, A2, B1, and B2), where each family is designed around a set of consistent assumptions: for example, a world that is more integrated or more divided. In contrast, the RCP scenarios are simply numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square meter) that results by 2100. This figure compares SRES and RCP annual carbon emissions (top), carbon dioxide equivalent levels in the atmosphere (middle), and temperature change that would result from the central estimate (lines) and the likely range (shaded areas) of climate sensitivity (bottom). At the top end of the range, the older SRES scenarios are slightly higher. Comparing carbon dioxide concentrations and global temperature change between the SRES and RCP scenarios, SRES A1fI is similar to RCP 8.5; SRES A1B to RCP 6.0 and SRES B1 to RCP 4.5. The RCP 2.6 scenario is much lower than any SRES scenario because it includes the option of using policies to achieve net negative carbon dioxide emissions before end of century, while SRES scenarios do not. (Data from CMIP3 and CMIP5).

Projected Annually-Averaged Temperature ChangeProjections

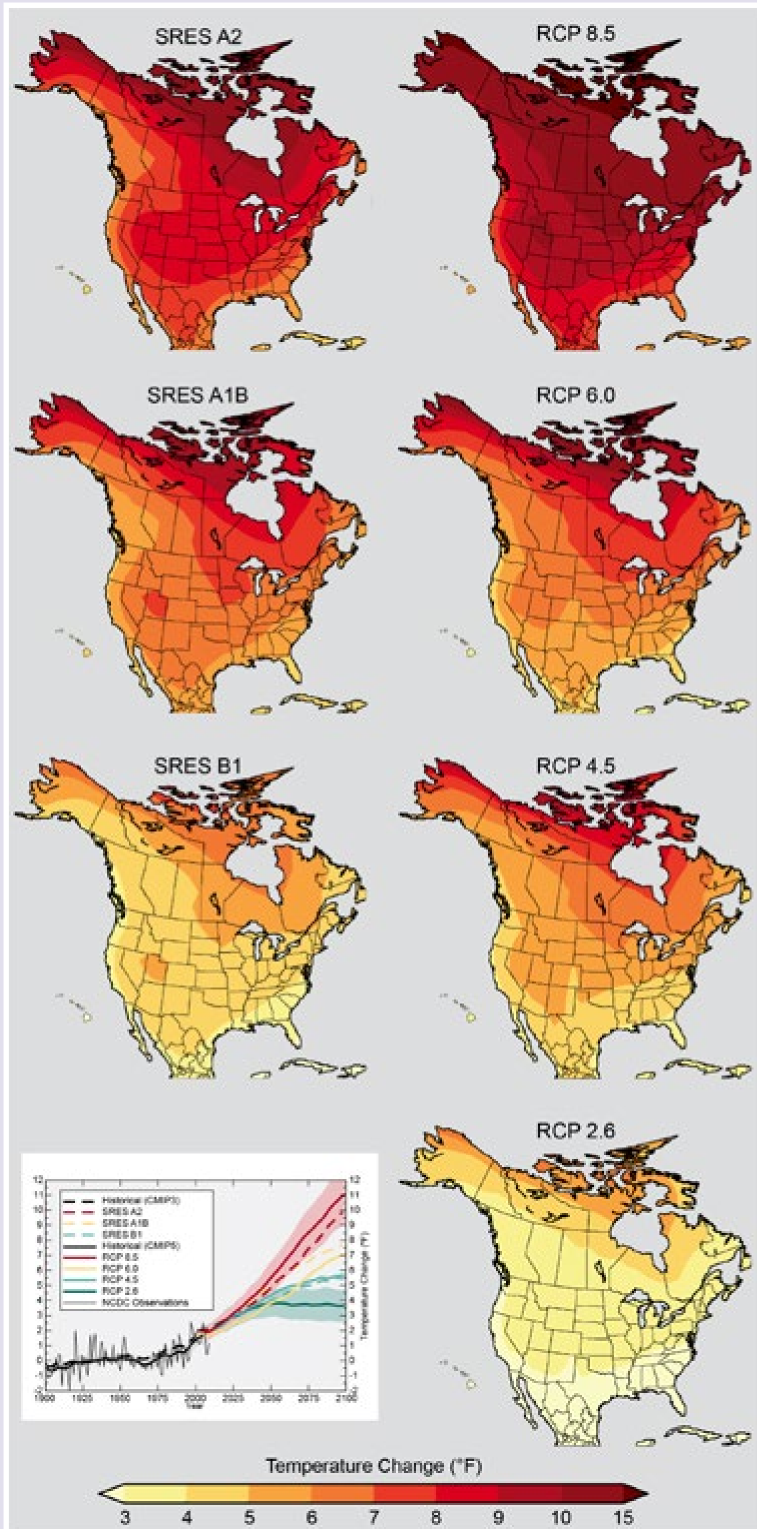


Figure 20. Projected change in surface air temperature at the end of this century (2071-2099) relative to the end of the last century (1970-1999). The older generation of models (CMIP3) and SRES emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. The scenarios are described under Supplemental Message 5 and in Figure 19. Differences between the old and new projections are mostly a result of the differences in the scenarios of the emission of heat-trapping gases rather than the increased complexity of the new models. None of the new scenarios are exactly the same as the old ones, although at the end of the century SRES B1 and RCP 4.5 are roughly comparable, as are SRES A1B and RCP 6.0. (Figure source: NOAA NCDC / CICS-NC).

Projected Wintertime Precipitation Changes

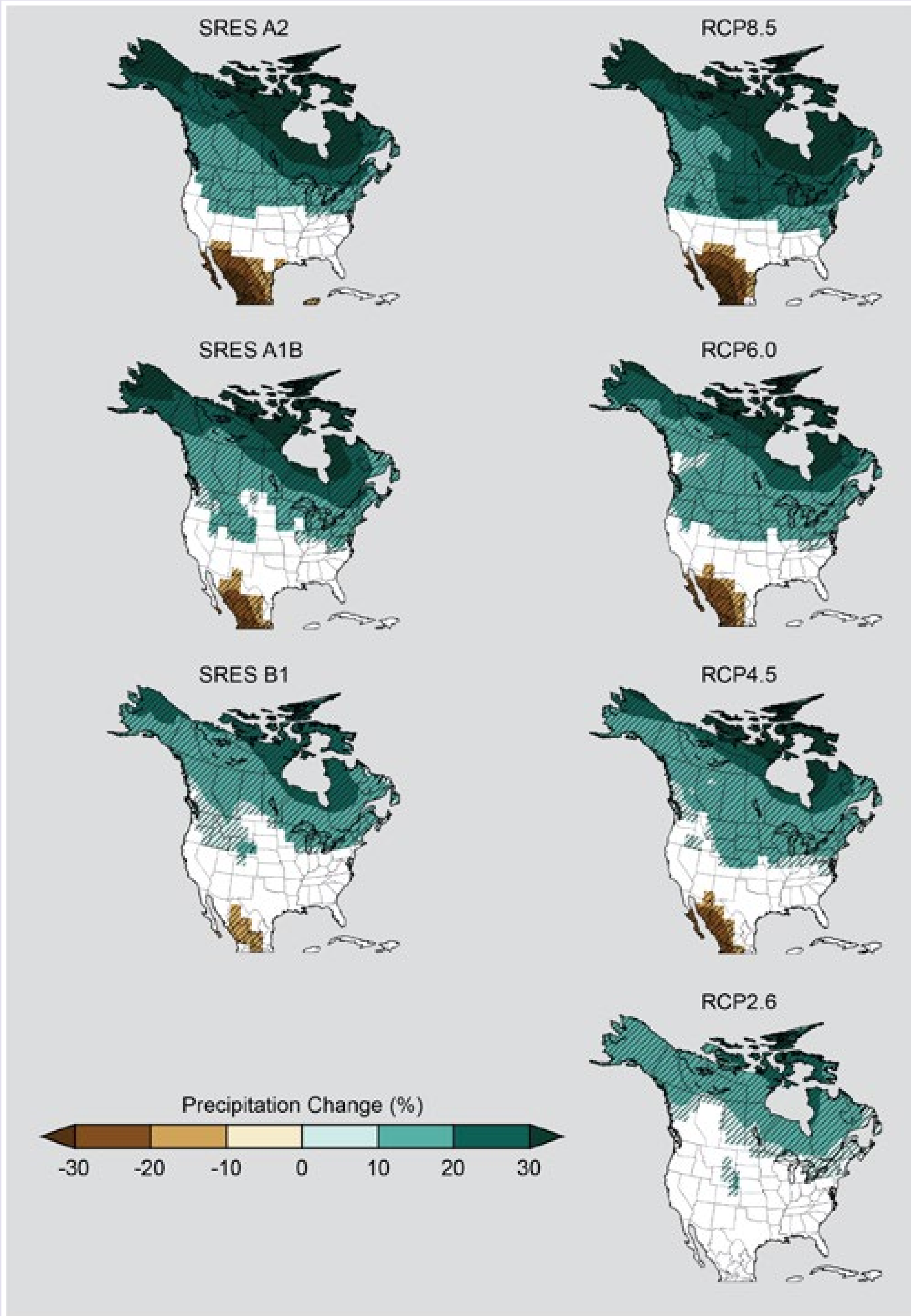


Figure 21. Projected changes in wintertime precipitation at the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In both sets of projections, the northern parts of the U.S. (and Alaska) become wetter. Increases in both the amount of precipitation change and the confidence in the projections go up as the projected temperature rises. In the farthest northern parts of the U.S., much of the additional winter precipitation will still fall as snow. This is not likely to be the case farther south. (Figure source: NOAA NCDC / CICS-NC).

Projected Summertime Precipitation Changes

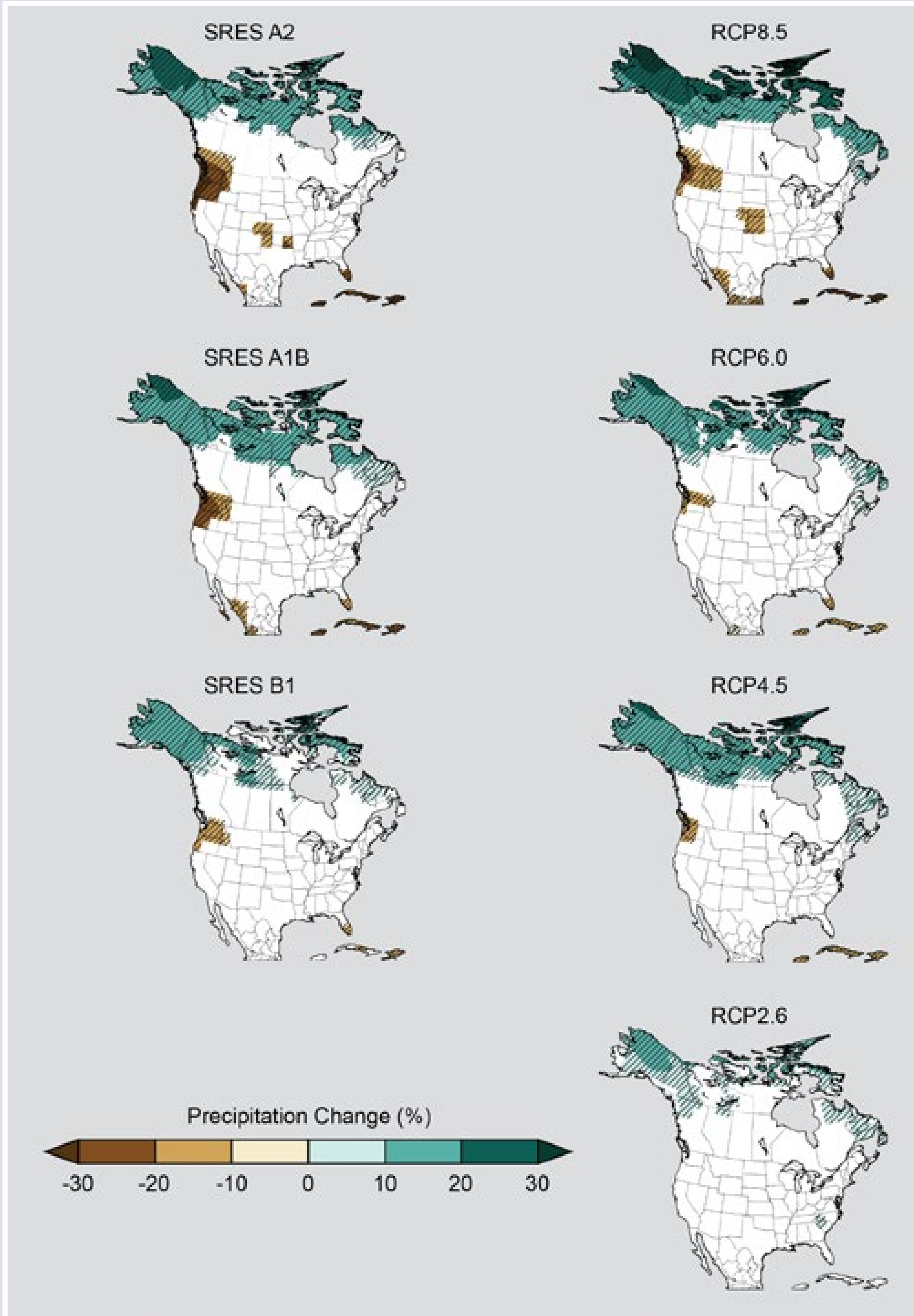


Figure 22. Projected changes in summertime precipitation toward the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate confidence that the changes are not projected to be larger than could be expected from natural variability. In most of the contiguous U.S., decreases in summer precipitation are projected, but not with as much confidence as the winter increases. When interpreting maps of temperature and precipitation projections, readers are advised to pay less attention to small details and greater attention to the large-scale patterns of change. (Figure source: NOAA NCDC / CICS-NC).

Carbon Emissions: Historical and Projected

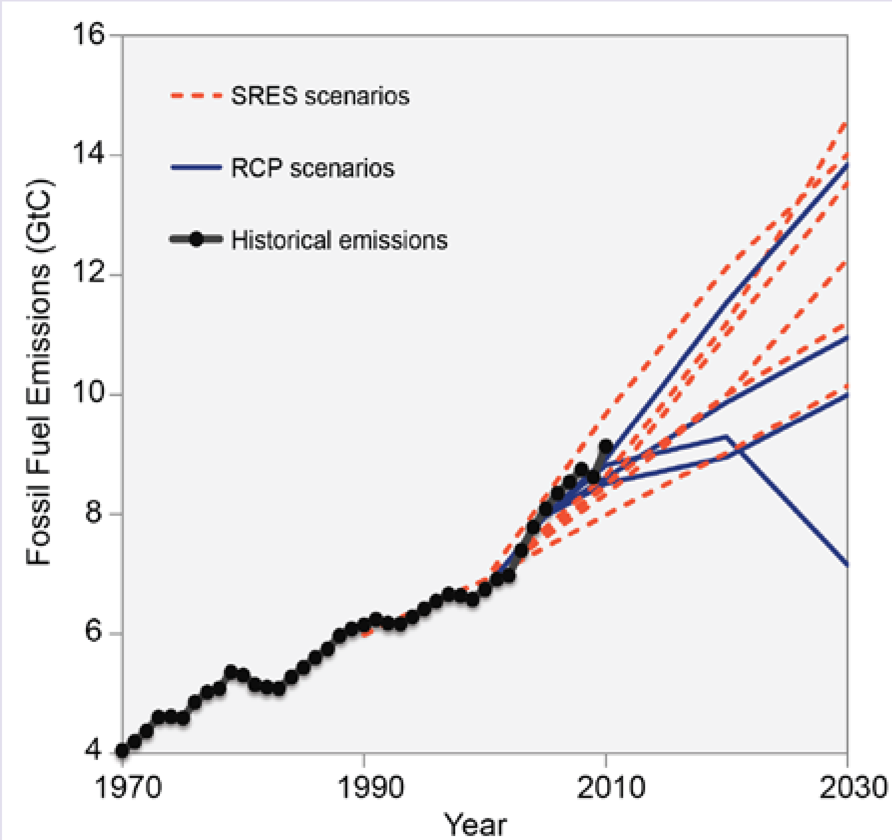


Figure 23. Historical emissions of carbon from fossil fuel (coal, oil, and gas) combustion and land-use change (such as deforestation) have increased over time. The growth rate was nearly three times greater during the 2000s as compared to the 1990s. This figure compares the observed historical (black dots) and projected future SRES (orange dashed lines) and RCP (blue solid lines) carbon emissions from 1970 to 2030. (Data from Boden et al. 2011[75] plus preliminary values for 2009 and 2010 based on BP statistics and U.S. Geological Survey cement data).

Supplemental Message 6.

Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.

Climate scientists use a wide range of observational and computational tools to understand the complexity of the Earth's climate system and to study how that system responds to external forces, including the effect of humans on climate. Observational tools are described in Supplemental Message 2.

Computational tools include models that simulate different parts of the climate system. The most sophisticated computational tools used by climate scientists are **global climate models** (previously referred to as "general circulation models"), or GCMs. Global climate models are mathematical models that simulate the physics, chemistry, and, increasingly, the biology that influence the climate system. GCMs are built on fundamental equations of physics that include the conservation of energy, mass, and momentum, and how these are exchanged among different parts of the climate system. Using these fundamental relationships, the models generate many important features that are evident in the Earth's climate system: the jet stream that circles the globe 30,000 feet above the Earth's surface; the Gulf Stream and other ocean currents that transport heat from the tropics to the poles; and even, when the models can be run at a fine enough spatial resolution to capture these features, hurricanes in the Atlantic and typhoons in the Pacific.

GCMs and other physical models are subject to two main types of uncertainty. First, because scientific understanding of the climate system is not complete, a model may not include an important process. This could be because that process is not yet recognized, or because it is known but is not yet understood well enough to be modeled accurately. For example, the models do not currently include adequate treatments of dynamical mechanisms that are important to melting ice sheets. The existence of these mechanisms is known, but they are not yet well enough understood to simulate accurately at the global scale. Also, observations of climate change in the distant past suggest there might be "tipping points," or mechanisms of abrupt changes in climate change, such as shifts in ocean circulation, that are not adequately understood.[76] These are discussed further in Appendix 4: FAQ T.

Second, many processes occur at finer temporal and spatial (time and space) scales than models can resolve. Models instead must approximate what these processes would look like at the spatial scale that the model can resolve using empirical equations, or parameterizations, based on a combination of observations and scientific understanding. Examples of important processes that must be parameterized in climate models include turbulent mixing, radiational heating/cooling, and small-scale physical processes such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere. For example, these models cannot represent every raindrop. However, they can simulate the total amount of rain that would fall over a large area the size of a grid cell in the model. These approximations are usually derived from a limited set of observations and/or higher resolution modeling and may not hold true for every location or under all possible conditions.

GCMs are constantly being enhanced as scientific understanding of climate improves and as computational power increases. For example, in 1990, the average model divided up the world into grid cells measuring more than 300 miles per side. Today, most models divide the world up into grid cells of about 60 to 100 miles per side, and some of the most recent models are able to run short simulations with grid cells of only 15 miles per side. Supercomputer capabilities are the primary limitation on grid cell size. Newer models also incorporate more of the physical processes and components that make up the Earth's climate system. The very first global climate models were designed to simulate only the circulation of the atmosphere. Over time, the ocean, clouds, land surface, ice, snow, and other features were added one by one. Most of these features were new modules that were developed by experts in those fields and then added into an existing GCM framework. Today, there are more than 35 GCMs created and maintained by more than 20 modeling groups around the world. Some of the newest models are known as Earth System Models, or ESMs, which include all the previous components of a typical GCM but also incorporate modules that represent additional aspects of the climate system, including agriculture, vegetation, and the carbon cycle.

Some models are more successful than others at reproducing observed climate and trends over the past century,[77] or the large-scale dynamical features responsible for creating the average climate conditions over a certain region (such as the Arctic[78] or the Caribbean[79]). Evaluation of models' success often depends on the variable or metric being considered in the analysis, with some models performing better than others for certain regions or variables.[80] However, all future simulations agree that both global and regional temperatures will increase over this century in response to increasing emissions of heat-trapping gases from human activities.[15]

Differences among model simulations over several years to several decades arise from natural variability (as discussed in Supplemental Message 3) as well as from different ways models characterize various small-scale processes. Averaging simulations from multiple models removes the effects of randomly occurring natural variations. The timing of natural variations is largely unpredictable beyond several seasons (although such predictability is an active research area). For this reason, model simulations are generally averaged (as the last stage in any analysis) to make it easier to discern the impact of external forcing (both human and natural). The effect of averaging on the systematic errors depends on the extent to which models have similar errors or offsetting errors.

Despite their increasing resolution, most GCMs cannot simulate fine-scale changes at the regional to local scale. For that reason, **downscaling** is often used to translate GCM projections into the high-resolution information required as input to impact analyses. There are two types of models commonly used for downscaling: dynamical and statistical.

Dynamical downscaling models are often referred to as regional climate models since they include many of the same physical processes that make up a global climate model, but simulate these processes at higher resolution and over a relatively small area, such as the Northwest or Southeast United States. At their boundaries, regional climate models use output from GCMs to simulate what is going on in the rest of the world. Regional climate models are computationally intensive, but provide a broad range of output variables including atmospheric circulation, winds, cloudiness, and humidity at spatial scales ranging from about 6 to 30 miles per grid cell. They are also subject to the same types of uncertainty as a global model, such as not fully resolving physical processes that occur at even smaller scales. Regional climate models have additional uncertainty related to how often their boundary conditions are updated and where they are defined. These uncertainties can have a large impact on the precipitation simulated by the models at the local to regional scale. Currently, a limited set of regional climate model simulations based on one future scenario and output from five CMIP3 GCMs is available from the North American Regional Climate Change Assessment Program (these are the "NARCCAP" models used in some sections of this report). These simulations are useful for examining certain impacts over North America. However, they do not encompass the full range of uncertainty in future projections due to both human activities and climate sensitivity described in Supplemental Message 5.

Statistical downscaling models use observed relationships between large-scale weather features and local climate to translate future projections down to the scale of observations. Statistical models are generally very effective at removing errors in historical simulated values, leading to a good match between the average (multi-decadal) statistics of observed and statistically downscaled climate at the spatial scale and over the historical period of the observational data used to train the statistical model. However, statistical models are based on the key assumption that the relationship between large-scale weather systems and local climate will remain constant over time. This assumption may be valid for lesser amounts of change, but could lead to errors, particularly in precipitation extremes, with larger amounts of climate change.[81] Statistical models are generally flexible and less computationally demanding than regional climate models. A number of databases provide statistically downscaled projections for a continuous period from 1960 to 2100 using many global models and a range of higher and lower future scenarios (for example, the U.S. Geological Survey database described by Maurer et al. 2007[82]).[83,84] Statistical downscaling models are best suited for analyses that require a range of future projections that reflect the uncertainty in emissions scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes.

Ideally, climate impact studies could use both statistical and dynamical downscaling methods. Regional climate models can directly simulate the response of regional climate processes to global change, while statistical models can better remove any biases in simulations relative to observations. However, rarely (if ever) are the resources available to take this approach. Instead, most assessments tend to rely on one or the other type of downscaling, where the choice is based on the needs of the assessment. If the study is more of a sensitivity analysis, where using one or two future simulations is not a limitation, or if it requires many climate variables as input, then regional climate modeling may be more appropriate. If the study needs to resolve the full range of projected changes under multiple models and scenarios or is more constrained by practical resources, then statistical downscaling may be more appropriate. However, even within statistical downscaling, selecting an appropriate method for any given study depends on the questions being asked. The variety of techniques ranges from a simple "delta" (change or difference) approach (subtracting historical simulated values from future values, and adding the resulting delta to historical observations, as used in the first national climate assessment[85]) to complex clustering and neural network techniques that rival dynamical downscaling in their demand for computational resources and high-frequency model output (for example, Kostopoulou and Jones 2007[86]; Vrac et al. 2007[81]). The delta approach is adequate for studies that are only interested in changes in seasonal or annual average temperature. More complex methods must be used for studies that require information on how climate change may affect the frequency or timing of precipitation and climate extremes.

Modeling the Climate System

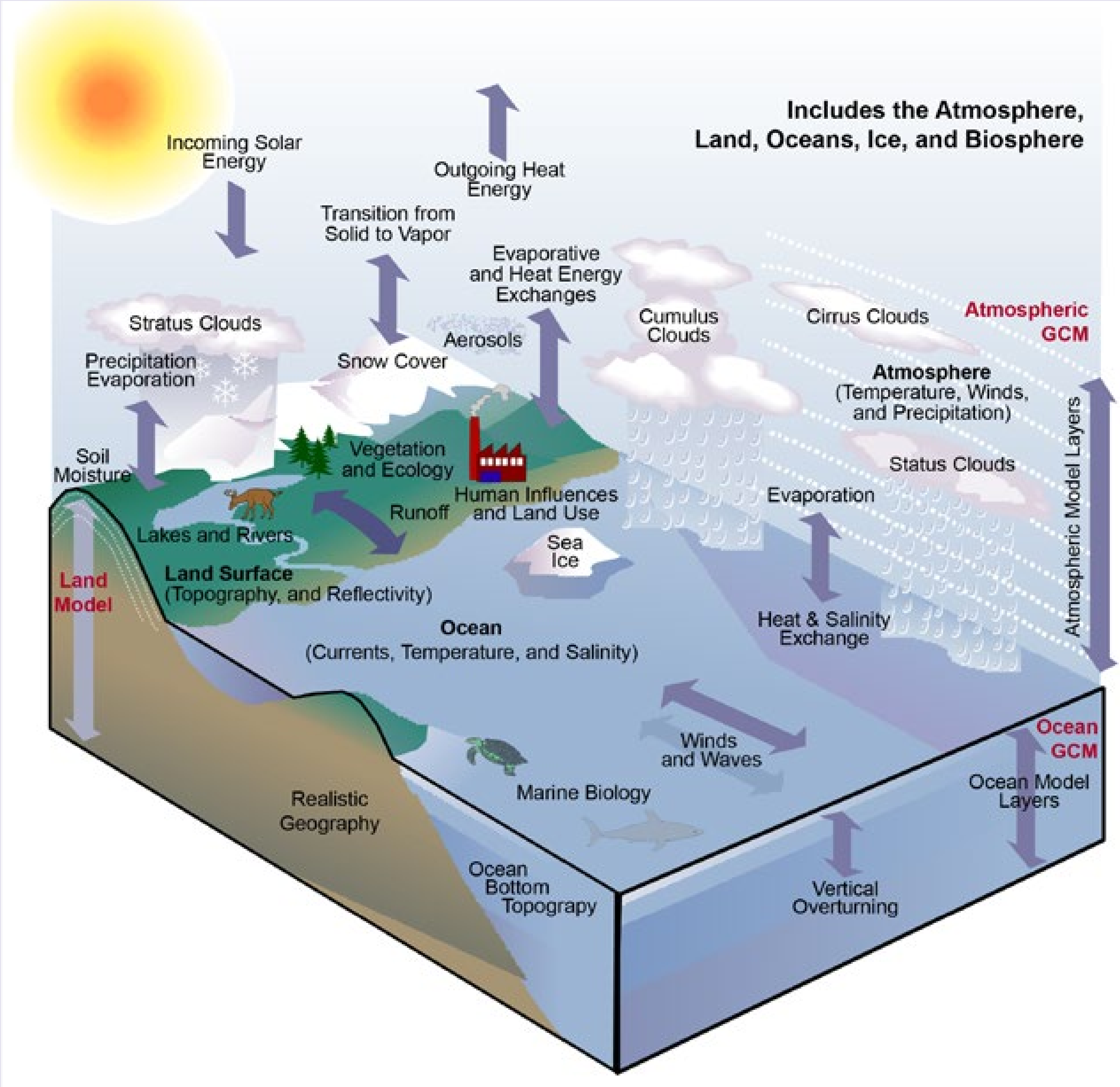


Figure 24. Some of the many processes often included in models of the Earth's climate system. (Figure source: Karl and Trenberth 2003[87]).

Increasing Model Resolution

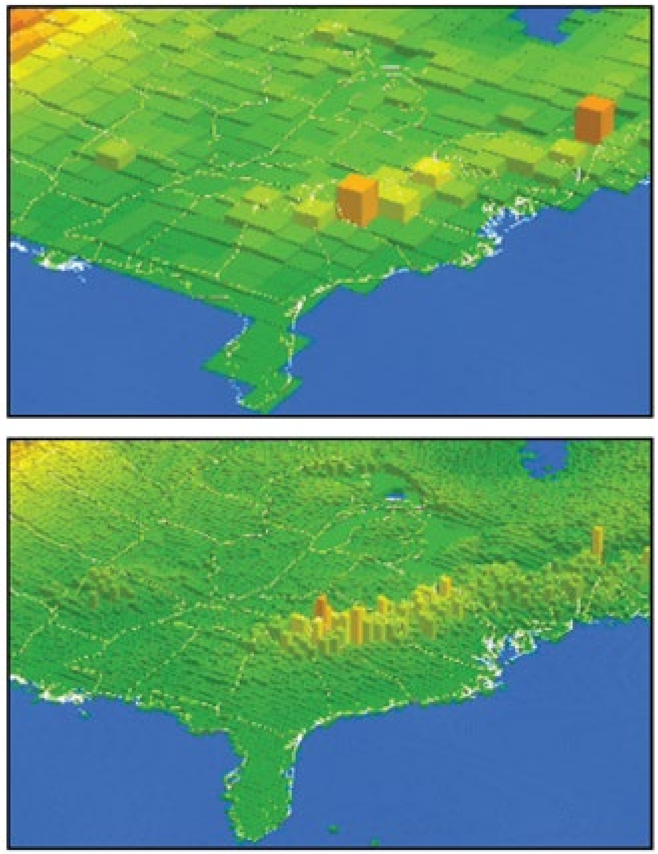
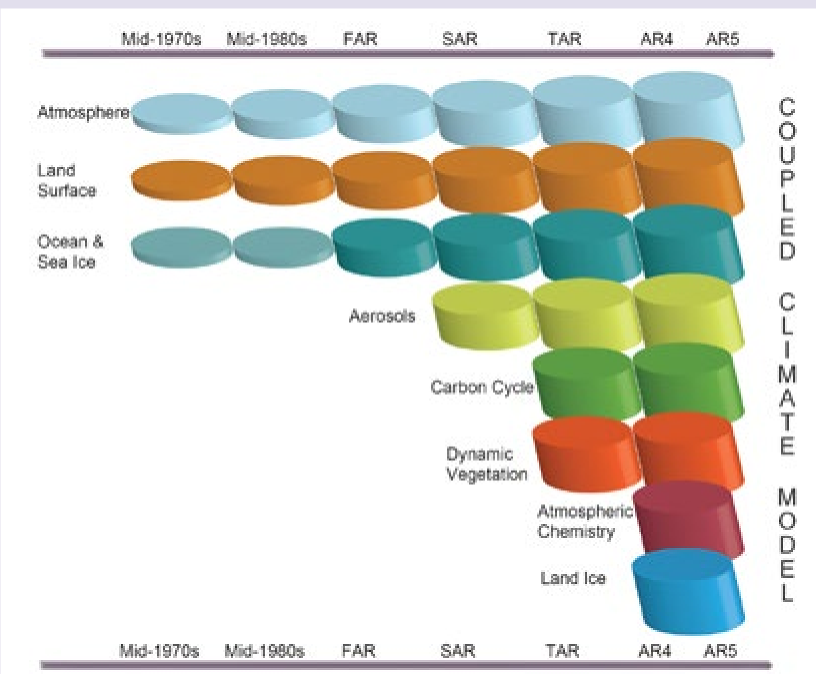


Figure 25. Top: Illustration of the eastern North American topography in a resolution of 68 x 68 miles (110 x 110 km). Bottom: Illustration of the eastern North American topography in a resolution of 19 x 19 miles (30 x 30 km).

Increasing Climate Model Components



Intergovernmental Panel on Climate Change Reports	
FAR	1990
SAR	1995
TAR	2001
AR4	2007
AR5	2013

Figure 26. The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (for example, the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably. (Figure source: adapted from Cubasch et al. 2013[88]).

Supplemental Message 7.

Scientific understanding of observed temperature changes in the United States has greatly improved, confirming that the U.S. is warming due to heat-trapping gas emissions, consistent with the climate change observed globally.

There have been substantial recent advances in our understanding of the continental U.S. temperature records. Numerous studies have looked at many different aspects of the record.[28,89,90,91,92,93] These studies have increased confidence that the U.S. is warming, and refined estimates of how much.

Historical temperature data are available for thousands of weather stations. However, for a variety of practical and often unavoidable reasons, there have been frequent changes to individual stations and to the network as a whole. Two changes are particularly important. The first is a widespread change in the time at which observers read their thermometers. Second, most stations now use electronic instruments rather than traditional glass thermometers.

Extensive work has been done to document the effect of these changes on historical temperatures. For example, the change from afternoon to morning observations resulted in systematically lower temperatures for both maximum and minimum, artificially cooling the U.S. temperature record by about 0.5°F.[93,94] The change in instrumentation was equally important but more complex. New electronic instruments generally recorded higher minimum temperatures, yielding an artificial warming of about 0.25°F, and lower maximum temperatures, resulting in an artificial cooling of about 0.5°F. This has been confirmed by extended period side-by-side instrument comparisons.[95] Confounding this, as noted by a recent citizen science effort, the new instruments were often placed nearer buildings or other man-made structures.[96] Analyses of the changes in siting indicate that this had a much smaller effect than the change in instrumentation across the network as a whole.[89,91,93]

Extensive work has been done to develop statistical adjustments that carefully remove these and other non-climate elements that affect the data. To confirm the efficacy of the adjustments, several sensitivity assessments have been undertaken. These include:

- a comparison with the U.S. Climate Reference Network;[91,97]
- analyses to evaluate biases and uncertainties;[93]
- comparisons to a range of state-of-the-art meteorological data analyses;[92] and
- in-depth analyses of the potential impacts of urbanization.[90]

These assessments agree that the corrected data do not overestimate the rate of warming. Rather, because the average effect of these issues was to reduce recorded temperatures, adjusting for these issues tends to reveal a larger long-term warming trend. The impact is much larger for maximum temperature as compared to minimum temperature because the adjustments account for two distinct artificial cooling signals: the change in observation time and the change in instrumentation. The impact is smaller for minimum temperature because the artificial signals roughly offset one another (the change in observation time cooling the record, the change in instrumentation warming the record). Even without these adjustments, however, both maximum and minimum temperature records show increases over the past century.

Geographically, maximum temperature has increased in most areas except in parts of the western Midwest, northeastern Great Plains, and the Southeast regions. Minimum temperature exhibits the same pattern of change with a slightly greater area of increases. The causes of these slight differences between maximum and minimum temperature are a subject of ongoing research.[98] In general, the uncorrected data exhibit more extreme trends as well as larger spatial variability; in other words, the adjustments have a smoothing effect.

The corrected temperature record also confirms that U.S. average temperature is increasing in all four seasons. The heat that occurred during the Dust Bowl era is prominent in the summer record. The warmest summer on record was 1936, closely followed by 2011. However, twelve of the last fourteen summers have been above average. Temperatures during the other seasons have also generally been above average in recent years.

Trends in Maximum and Minimum Temperatures

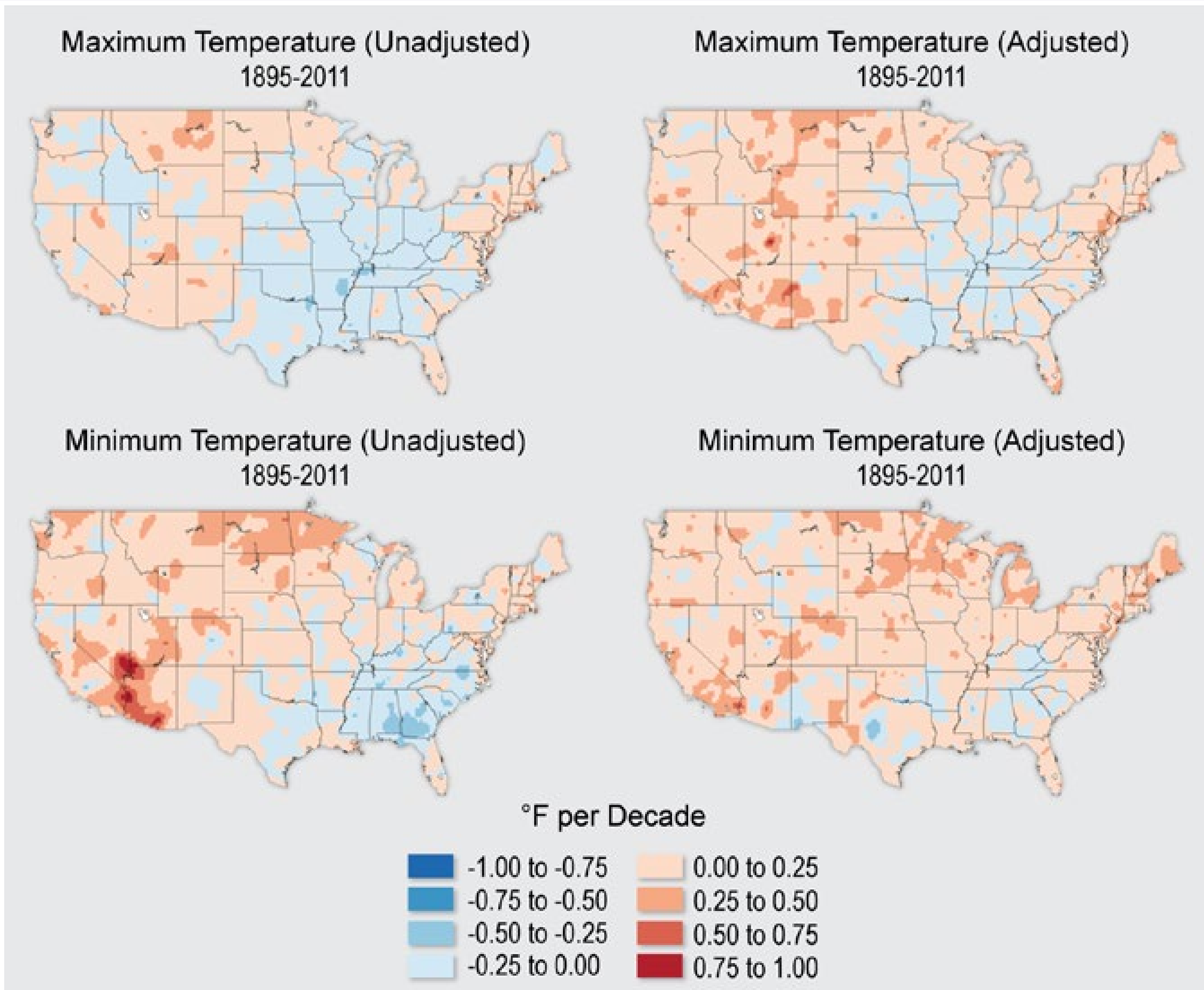


Figure 27. Geographic distribution of linear trends in the U.S. Historical Climatology Network for the period 1895-2011. (Figure source: updated from Menne et al. 2009[91]).

U.S. Seasonal Temperatures

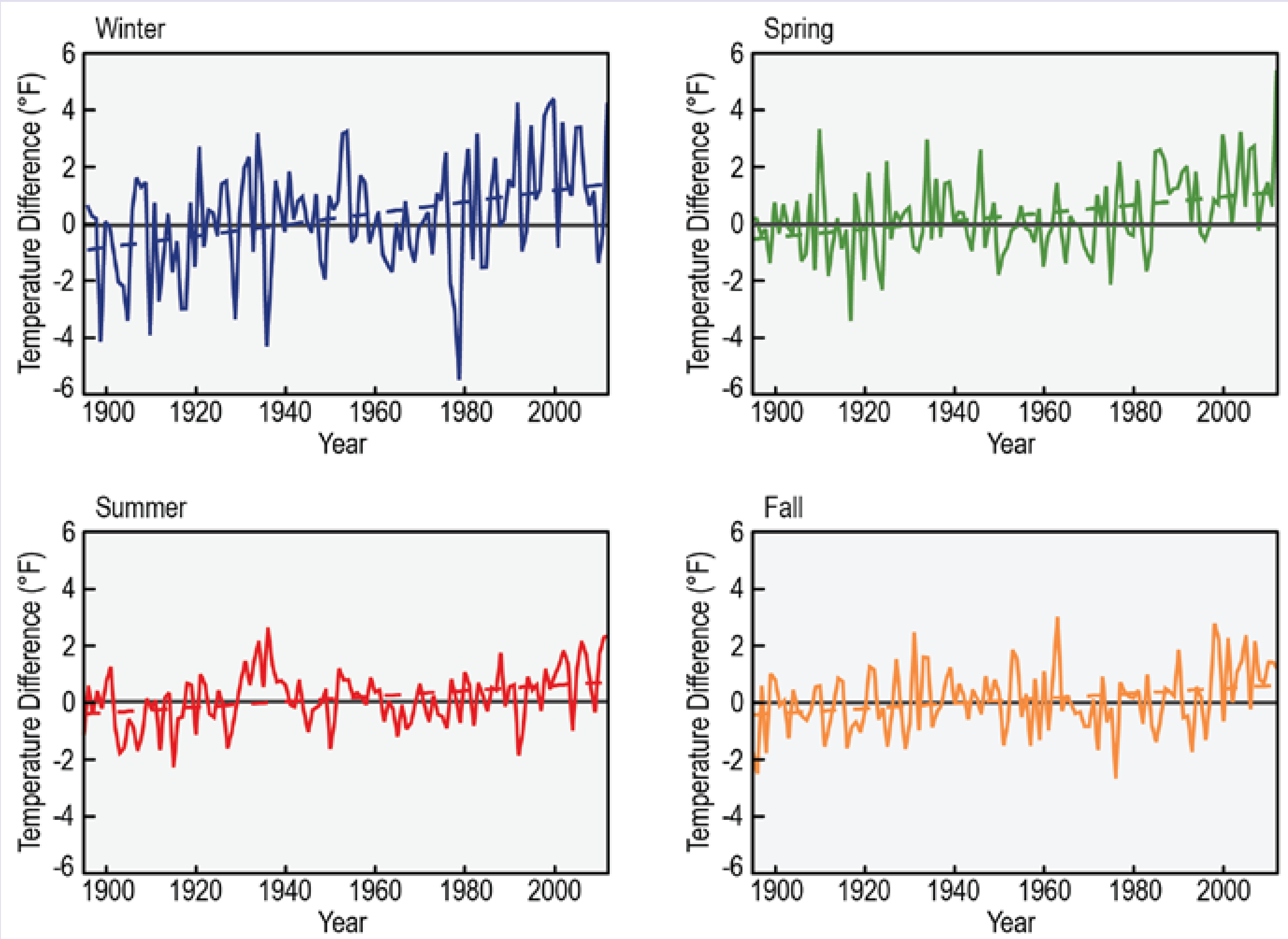


Figure 28. Continental U.S. seasonal temperatures (relative to the 1901-1960 average) for winter, spring, summer, and fall all show evidence of increasing trends. Dashed lines show the linear trends. Stronger trends are seen in winter and spring as compared to summer and fall. (Figure source: updated from Kunkel et al. 2013[99]).

Supplemental Message 8.

Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.

While surface air temperature is the most widely cited measure of climate change, other aspects of climate that are affected by temperature are often more directly relevant to both human society and the natural environment. Examples include shorter duration of ice on lakes and rivers, reduced glacier extent, earlier melting of snowpack, reduced lake levels due to increased evaporation, lengthening of the growing season, and changes in plant hardiness zones. Changes in these and many other variables are consistent with the recent warming over much of the United States. Taken as a whole, these changes provide compelling evidence that increasing temperatures are affecting both ecosystems and human society.

Striking decreases in the coverage of ice on the Great Lakes have occurred over the last few decades (see Ch 2: Our Changing Climate, Key Message 11). The annual average ice cover area for the Great Lakes, which typically shows large year-to-year variability, has sharply declined over the last 30+ years.[100] Based on records covering the winters of 1972-1973 through 2010-2011, 12 of the 19 winters prior to 1991-1992 had annual average ice cover greater than 20% of the total lake area while 15 of the 20 winters since 1991-1992 have had less than 20% of the total lake area covered with ice. This includes the three lowest ice extent winters of 1997-1998, 2001-2002, and 2005-2006. A reduction in ice leading to more open water in winter raises concerns about possible increases in lake effect snowfall, although future trends will also depend on the difference between local air and water temperatures.

Smaller lakes in other parts of the country show similar changes. For example, the total duration of ice cover on Lake Mendota in Madison, Wisconsin, has decreased from about 120 days in the late 1800s to less than 100 days in most years since 1990.[101] Average dates of spring ice disappearance on Minnesota lakes show a trend toward earlier melting over the past 60 years or so. These changes affect the recreational and commercial activities of the surrounding communities.

A long-term record of the ice-in date (the first date in winter when ice coverage closes the lake to navigation) on Lake Champlain in Vermont shows that the lake now freezes approximately two weeks later than in the early 1800s and over a week later than 100 years ago.[102] Later ice-in dates are an indication of higher lake temperatures, as it takes longer for the warmer water to freeze in winter. Prior to 1950, the absence of winter ice cover on Lake Champlain was rare, occurring just three times in the 1800s and four times between 1900 and 1950. By contrast, it remained ice-free during 42% of the winters between 1951 and 1990, and since 1991, Lake Champlain has remained ice-free during 64% of the winters. One- to two-week advances of ice breakup dates and similar length delays of freeze-up dates are also typical of lakes and rivers in Canada, Scandinavia, and northern Asia.[15]

While shorter durations of lake ice enhance navigational opportunities during winter, decreasing water levels in the Great Lakes present risks to navigation, especially during the summer. Water levels on Lakes Superior, Michigan, and Ontario have been below their long-term (1918-2008) averages for much of the past decade.[103] The summer drought of 2012 left Lakes Michigan and Ontario approximately one foot below their long-term averages. As noted in the second national climate assessment,[1] projected water level reductions for this century in the Great Lakes range from less than a foot under lower emissions scenarios to between 1 and 2 feet under high-

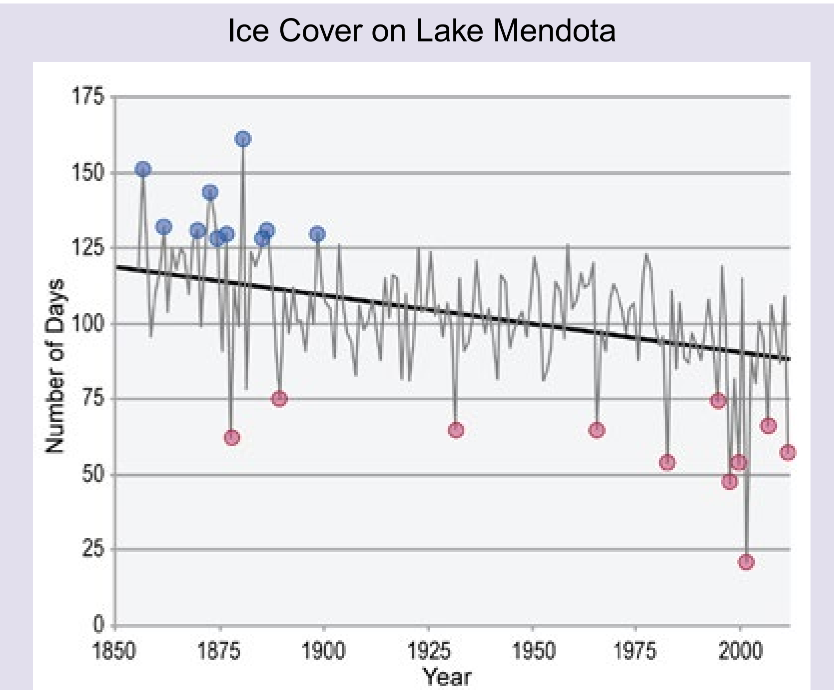


Figure 29. The duration, or number of days, of ice cover on Lake Mendota, Wisconsin, has decreased over time. The 10 longest ice seasons are marked by blue circles, and the 11 shortest ice seasons are marked by red circles. Seven of the 10 shortest ice cover seasons have occurred since 1980. (Figure source: Kunkel et al. 2013[107]).

Streamflow from Snowmelt Coming Earlier in the Year

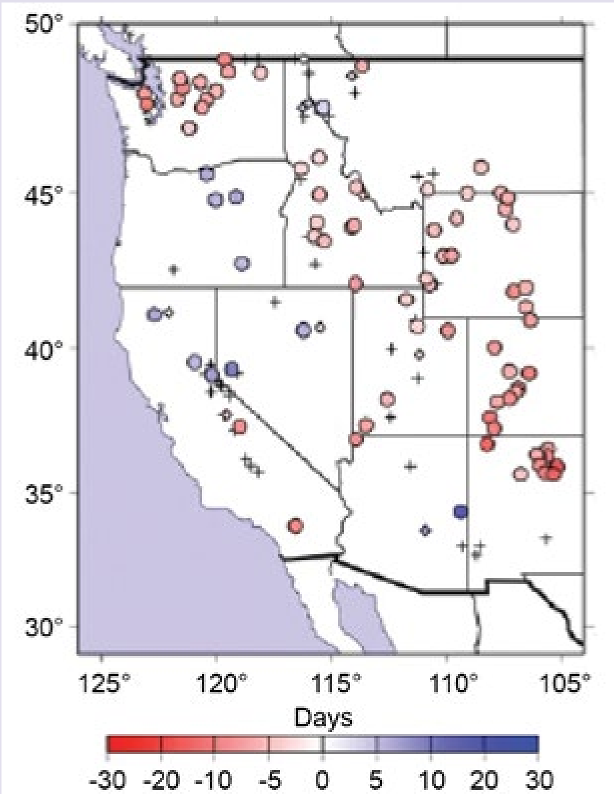


Figure 30. At many locations in the western U.S., the timing of streamflow in rivers fed by snowpack is shifting to earlier in the year. Red dots indicate stream gauge locations where half of the annual flow is now arriving anywhere from 5 to 20 days earlier each year for 2001-2010, relative to the 1951-2000 average. Blue dots indicate locations where the annual flow is now arriving later. Crosses indicate locations where observed changes are not statistically different from the past century baseline at 90% confidence levels, diamonds indicate gauges where the timing difference was significantly different at 90% confidence, and dots indicate gauges where timing was different at 95% confidence level. (Updated from Stewart et al. 2005[110]).

er emissions scenarios, with the smallest changes projected for Lake Superior and the largest change projected for Lakes Michigan and Huron.[83] A notable feature is the large range (several feet) of water level projections among models.[104] More recent studies have indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[105] Accounting for land-atmosphere feedbacks may further reduce the estimates of lake level declines.[106] These recent studies, along with the large spread in models, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty.

In the U.S. Southwest, indications of a changing climate over the last five decades include decreases in mountain snowpack,[108] earlier dates of snowmelt runoff,[109,110] earlier onset of spring (as indicated by shifts in the timing of plant blooms and spring snowmelt-runoff pulses),[111] general shifts in western hydroclimatic seasons,[112] and trends toward more precipitation falling as rain instead of snow over the West.[113] The ratio of precipitation falling as rain rather than snow, the amount of water in snowpack, and the timing of peak stream flow on snowmelt-fed rivers all changed as expected with warming over the past dozen years, relative to the last century baselines.[62]

Changing temperatures affect vegetation through lengthening of the frost-free season and the corresponding growing season, and changing locations of plant tolerance thresholds. The U.S. average frost-free season length (defined as the number of days between the last and first occurrences of 32°F in spring and autumn, respectively) increased by about two weeks during the last century.[114] The increase was much greater in the western than in the eastern United States. Consistent with the recent observed trends in frost-free season length, the largest projected changes in growing season length are in the mountainous regions of the western United States, while smaller changes are projected for the Midwest, Northeast, and Southeast. Related plant and animal changes include a northward shift in the typical locations of bird species[115] and a shift since the 1980s toward earlier first-leaf dates for lilac and honeysuckle.[116]

Plant hardiness zones are determined primarily by the extremes of winter cold.[117] Maps of plant hardiness have guided the selection of plants for both ornamental and agricultural purposes, and these zones are changing as climate warms. Plant hardiness zones for the U.S. have recently been updated using the new climate normals (1981-2010), and these zones show a northward shift by up to 100 miles relative to the zones based on the older (1971-2000) normals. Even greater northward shifts, as much as 200 miles, are projected over the next 30 years as warming increases. Projected shifts are largest in the major agricultural regions of the central United States.

Evidence of a warming climate across the U.S. is based on a host of indicators: hydrology, ecology, and physical climate. Most of these are changing in ways consistent with increasing temperatures, and are expected to continue to change in the future as a result of ongoing increases in human-induced heat-trapping gas emissions.

Shifts in Plant Hardiness Zones

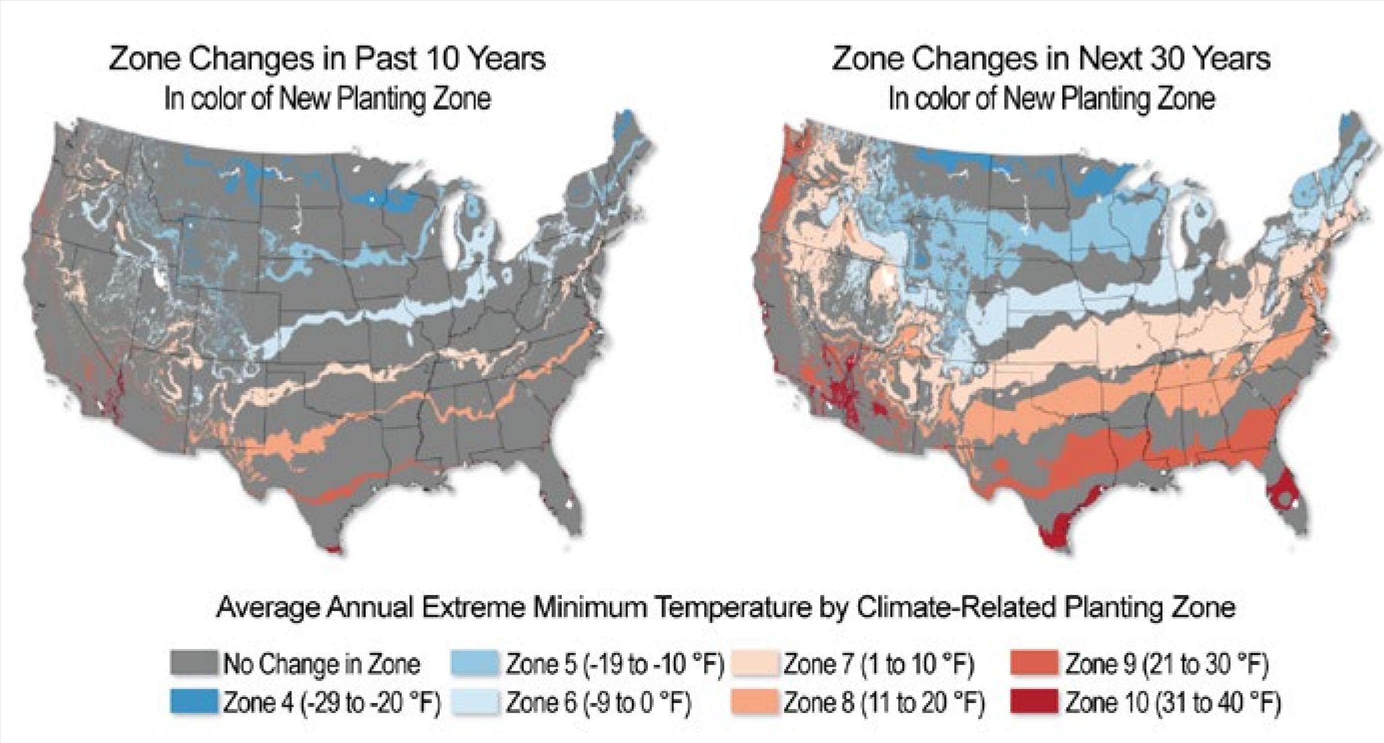


Figure 31. The map on the left shows the change in Plant Hardiness Zones calculated from those based on the 1971-2000 climate to those based on the 1981-2010 climate. Even greater changes are projected over the next 30 years (right). (Figure source: NOAA).

Supplemental Message 9.

Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate change's effects on other types of extreme events continues.

High impact, large-scale extreme events are complex phenomena involving various factors that can vcreate a "perfect storm." Such extreme weather occurs naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events.

Observations show that heavy downpours have already increased nationally. Regional and global models project increases in extreme precipitation for every U.S. region.[118] Precipitation events tend to be limited by available moisture. For the heaviest, most rare events, there is strong evidence from observations[119] and models[118,120] that higher temperatures and the resulting moister atmosphere are the main cause of these observed and projected increases. Other factors that may also have an influence on observed U.S. changes in extreme precipitation are land-use changes (for example, changes in irrigation[121,122]) and a shift in the number of El Niño events versus La Niña events.

Climate change can also alter the characteristics of the atmosphere in ways that affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an increasing trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms (also referred to as extra-tropical [outside the tropics] cyclones[123]). There is also a northward shift in storms over the U.S.[124] that are often associated with extreme precipitation. This shift is consistent with projections of a warming world.[125] No change in mid-latitude storm intensity or frequency has been detected.

In the tropics, the most important types of storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer Category 1 and 2 hurricanes and more Category 4 and 5 hurricanes. There has been no significant trend in the global number of tropical cyclones[126] nor has any trend been identified in the number of U.S. landfalling hurricanes.[1] Two

Extreme Precipitation

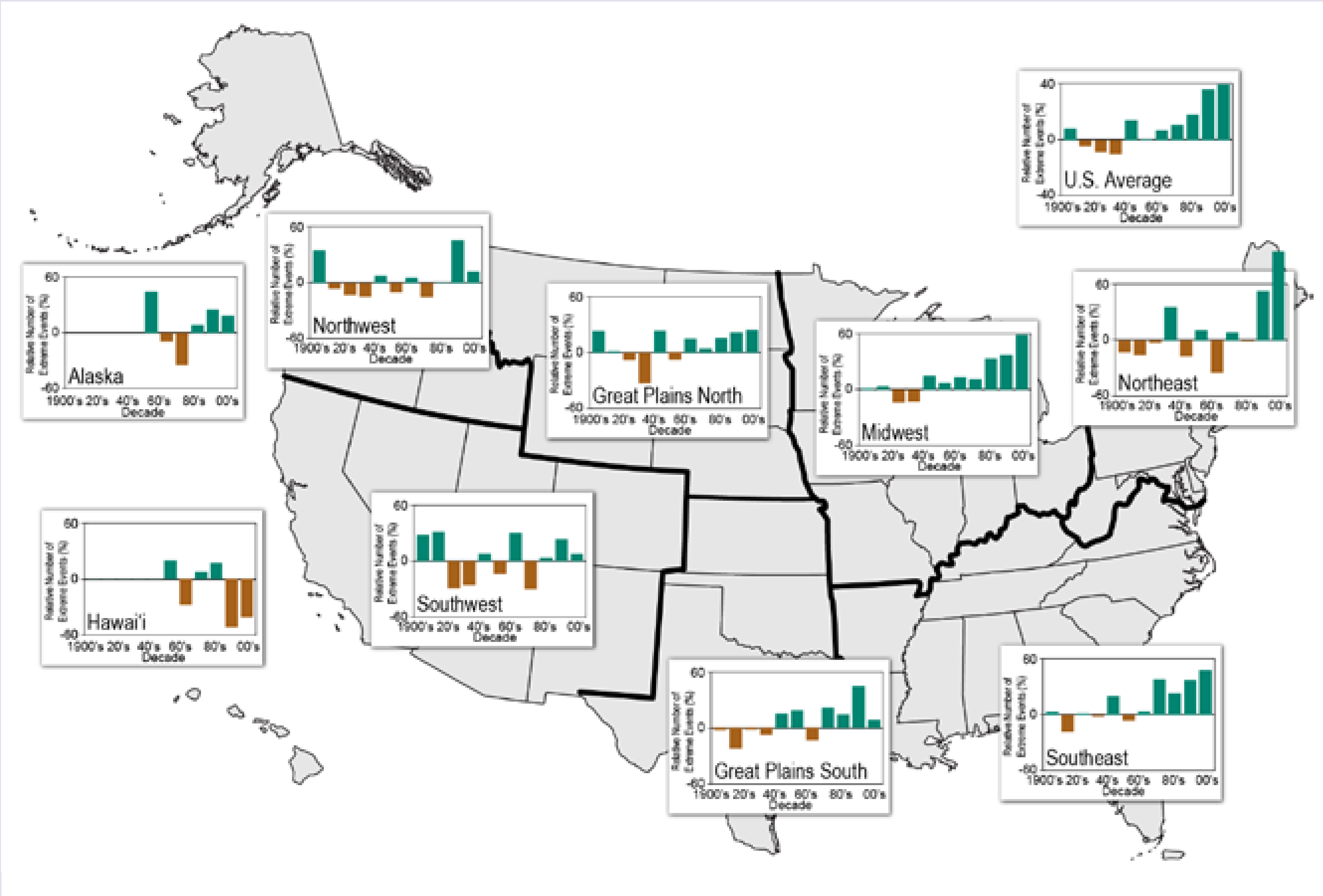


Figure 32. Heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast.[99] Despite considerable decadal-scale natural variability, indices such as this one based on 2-day precipitation totals exceeding a threshold for a 1-in-5-year occurrence exhibit a greater than normal occurrence of extreme events since 1991 in all U.S. regions except Alaska and Hawaiʻi. Each bar represents that decade's average, while the far right bar in each graph represents the average for the 12-year period of 2001-2012. Analysis is based on 726 long-term, quality-controlled station records. This figure is a regional expansion of the national index in Figure 2.16 of Chapter 2. (Figure source: updated from Kunkel et al. 2013[99]).

studies have found an upward trend in the number of extreme precipitation events associated with tropical cyclones,[127] but significant uncertainties remain.[122] A change in the number of Atlantic hurricanes has been identified, but interpreting its significance is complicated both by multi-decadal natural variability and the reliability of the pre-satellite historical record.[128] The global satellite record shows a shift toward stronger tropical cyclones,[126,129] but does not provide definitive evidence of a long-term trend. Nonetheless, there is a growing consensus based on scientific understanding and very-high-resolution atmospheric modeling that the strongest tropical cyclones, including Atlantic hurricanes, will become stronger in a warmer world.[130]

The number of heat waves has been increasing in recent years. On a decadal basis, the decade of 2001-2010 had the second highest number since 1901 (first is the 1930s). This trend has continued in 2011 and 2012, with the number of intense heat waves being almost triple the long-term average. Regionally, the Northwest, Southwest, and Alaska had their highest number of heat waves in the 2000s, while the 1930s were the highest in the other regions (note that the Alaskan time series begins in the 1950s). For the number of intense cold waves, the national-average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent throughout the contiguous U.S. and Alaska. Climate model simulations indicate that the recent trends toward increasing frequency of heat waves and decreasing frequency of cold waves will continue in the future.

The data on the number and intensity of severe thunderstorm phenomena (including tornadoes, thunderstorm winds, and hail) are not of sufficient quality to determine whether there have been historical trends.[119] This scarcity of high-quality data, combined with the fact that these phenomena are too small to be directly represented in climate models,[131] makes it difficult to project how these storms might change in the future.

Supplemental Message 10.

Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.

As temperatures rise, evaporation rates increase, which (all else remaining equal) would be expected to lead to increased drying.[131] The Palmer Drought Severity Index (PDSI),[132] a widely used indicator of dryness that incorporates both precipitation and temperature-based evaporation estimates, does not show any trend for the U.S. as a whole over the past century.[133] However, drought intensity and frequency have been increasing over much of the western United States, especially during the last four decades. In the Southeast, western Great Lakes, and southern Great Plains, droughts have increased during the last 40 years, but do not show an increase when examined over longer periods encompassing the entire last century. In the Southwest, drought has been widespread since 2000; the average value of the PDSI during the 2000s indicated the most severe average drought conditions of any decade. The severity of recent drought in the Southwest reflects both the decade's low precipitation and high temperatures.

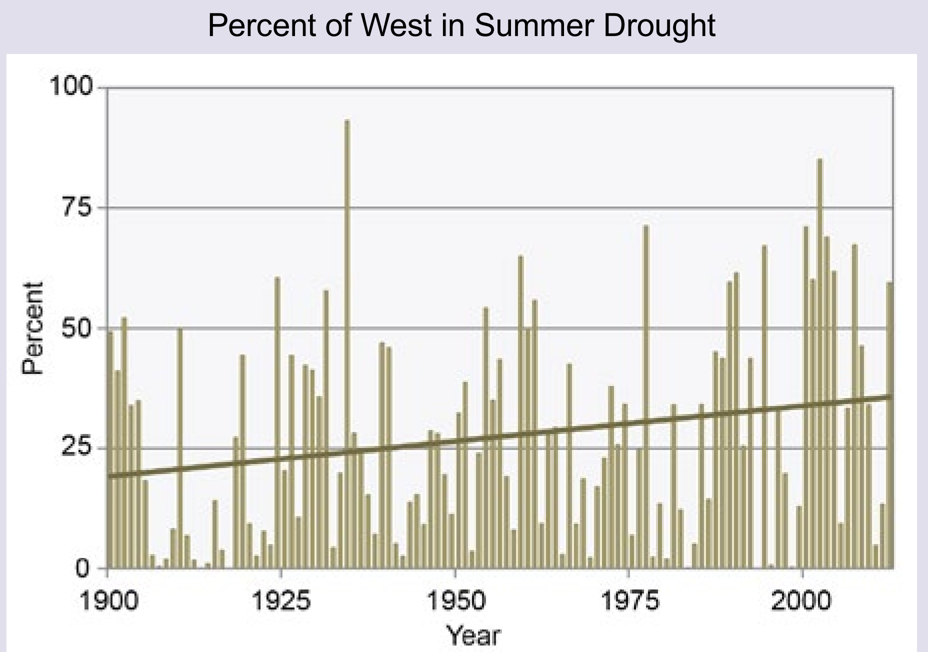


Figure 33. The area of the western U.S. in moderately to extremely dry conditions during summer (June-July-August) varies greatly from year to year but shows a long-term increasing trend from 1900 to 2012. (Data from NOAA NCDC State of the Climate Drought analysis).

Seasonal and multi-year droughts affect wildfire severity.[134] For example, persistent drought conditions in the Southwest, combined with wildfire suppression and land management practices,[135] have contributed to wildfires of unprecedented size since 2000. Five western states (Arizona, Colorado, Utah, California, and New Mexico) have experienced their largest fires on record at least once since 2000. Much of the increase in fires larger than 500 acres occurred in the western United States, and the area burned in the Southwest increased more than 300% relative to the area burned during the 1970s and early 1980s.[136]

Droughts on a duration and scale that affect agriculture are projected to increase in frequency and severity in this century due to higher temperatures. Projections of the Palmer Drought Severity Index at the end of this century indicate that the normal state for most of the nation will be what is considered moderate to severe drought today.[137,138] The PDSI is used by several states for monitoring drought and for triggering certain actions.[139] It is also one component of the U.S. Drought Monitor.[140] The closely related Palmer Hydrological Index is the most

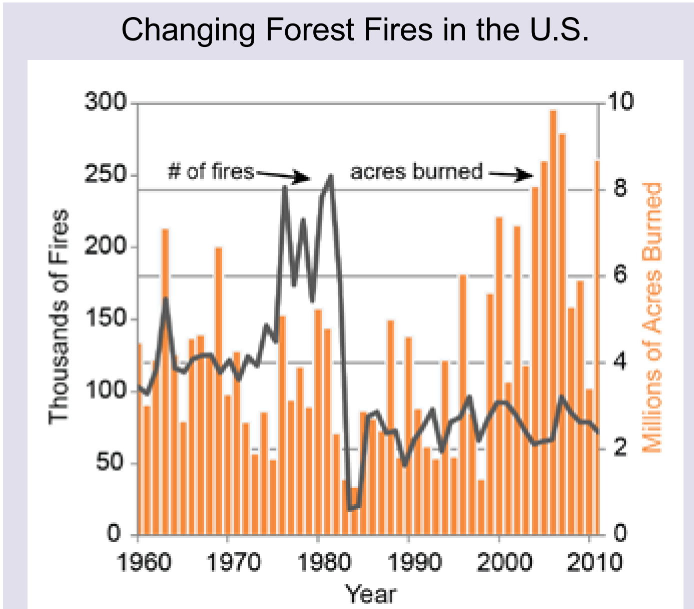


Figure 34. Although the average number of wildfires per year (black line) has decreased over time, the total area burned by wildfires (orange bars) in the continental U.S. (primarily in the western states) has nearly doubled since 2000 relative to the long-term 1960-1999 average (data shown are for 1960-2011). (Data from the National Interagency Fire Center).

Extreme Drought in the U.S. and Mexico, Past and Future

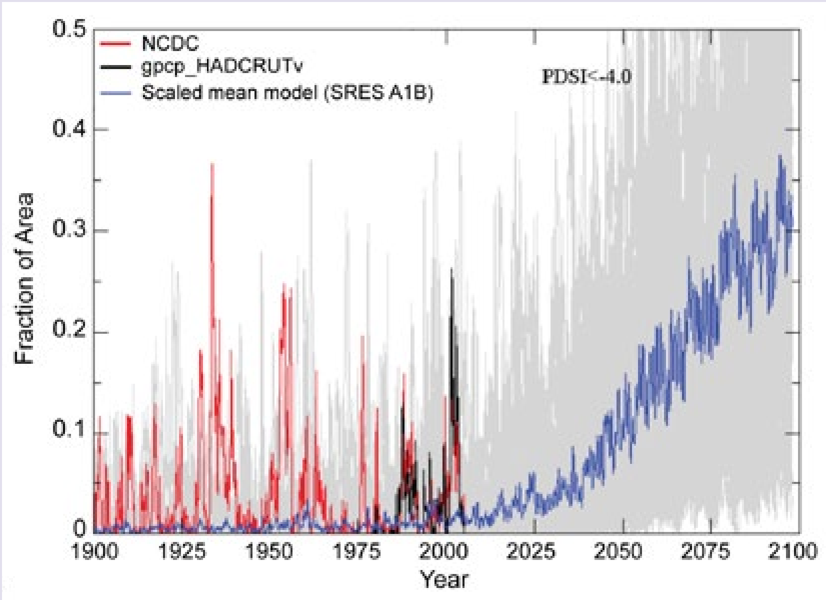


Figure 35. The fractional areal extent of the contiguous U.S. and Mexico in extreme drought according to projections of the Palmer Drought Severity Index under an intermediate emissions scenario (SRES A1B, in between the B1 and A2 scenarios used elsewhere in this report) (Supplemental Message 5 and Ch. 2: Our Changing Climate, Key Message 3). The Palmer Drought Severity Index is the most widely used measure of drought, although it is more sensitive to temperature than other drought indices and may over-estimate the magnitude of drought increases. The red line is based on observed temperature and precipitation. The blue line is from the average of 19 different climate models. The gray lines in the background are individual results from over 70 different simulations from these models. These results suggest an increasing probability of agricultural drought over this century throughout most of the U.S. (Figure source: Wehner et al. 2011[138]).

important component of NOAA's Objective Long-term Drought Indicator Blend,[141] which is used by the U.S. Department of Agriculture to identify counties that are eligible to participate in certain Federal Government drought relief programs. The U.S. Drought Monitor is used by some states for similar purposes.

Despite its widespread usage, the PDSI may be overly sensitive to future temperature increases.[142] As temperatures increase during this century, these PDSI-based monitoring tools may over-estimate the intensity of drought during anomalous warm periods, so statutory adjustments to these tools may be warranted. However, the projection of increased drought risk is reinforced by a direct examination of future soil moisture content projections, which reveals substantial drying in most areas of the western U.S (Ch. 2: Our Changing Climate, Key Message 3).

Provided the wood and ground litter has dried out, the area of forest burned in many mid-latitude areas, including the western United States, may increase substantially as temperature and evapotranspiration increase, exacerbating drought.[143] Under even relatively modest amounts of warming, significant increases in area burned are projected in the Sierra Nevada, southern Cascades, and coastal California; in the mountains of Arizona and New Mexico; on the Colorado Plateau; and in the Rocky Mountains.[144] Other studies, examining a broad range of climate change and development scenarios, find increases in the chance of large fires for much of northern California's forests.[145]

Long periods of consecutive days with little or no precipitation also can lead to drought. The average annual maximum number of consecutive dry days are projected to increase for the higher emissions scenarios in areas that are already prone to little precipitation by mid-century and increase thereafter (Ch. 2: Our Changing Climate, Key Message 5). Much of the western and southwestern U.S. is projected to experience statistically significant increases in the annual maximum number of consecutive dry days, on average up to 10 days above present-day values for parts of the contiguous U.S. by the end of this century under high emissions scenarios. Hence, some years are projected to experience substantially longer dry seasons.

Change in Maximum Number of Consecutive Dry Days

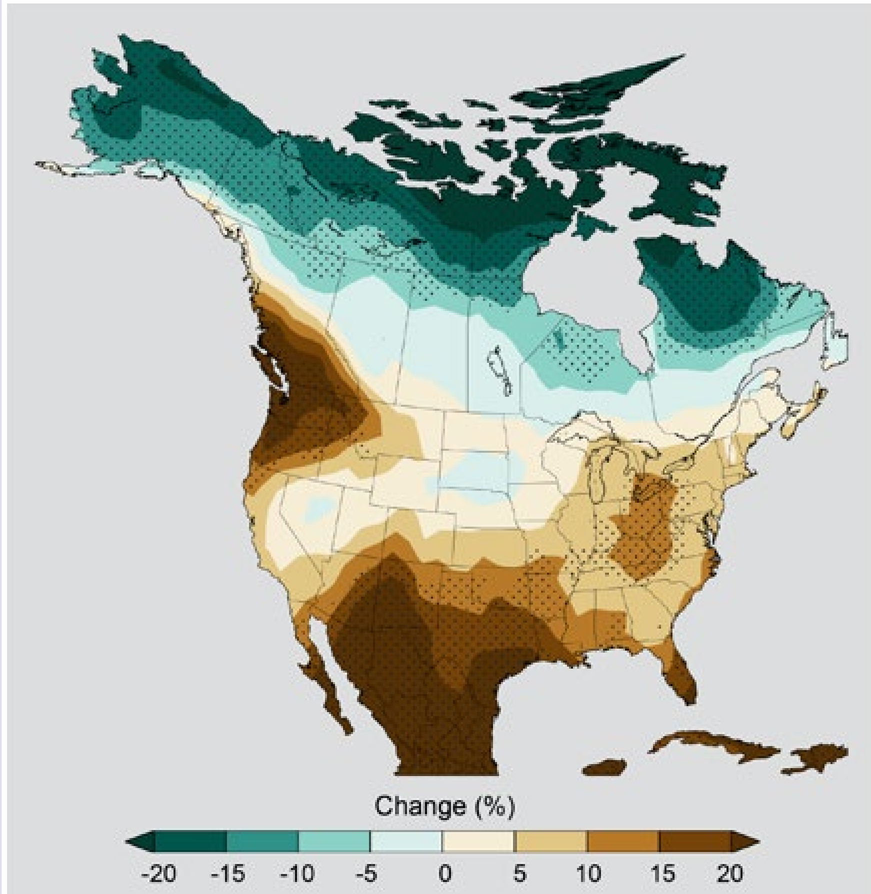


Figure 36. Change in the number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) at the end of this century (2081-2100) relative to the end of last century (1980-1999) under the higher scenario, RCP 8.5. Stippling indicates areas where changes are consistent among at least 80% of the 25 models used in this analysis. (Supplemental Message 5 and Ch. 2: Our Changing Climate, Key Message 3). (Figure source: NOAA NCDC / CICS-NC).

Supplemental Message 11.

Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

Increasing temperatures and associated impacts are apparent throughout the Arctic, including Alaska. Sea ice coverage and thickness, permafrost on land, mountain glaciers, and the Greenland Ice Sheet all show changes consistent with higher temperatures.

The most dramatic decreases in summer sea ice have occurred along the northern coastline of Alaska and Russia. Since the satellite record began in 1979, September (summer minimum) sea ice extent has declined by 13% per decade in the Beaufort Sea and 32% per decade in the Chukchi Sea,[146] leaving the Chukchi nearly ice-free in the past few Septembers. Longer-term records based on climate proxies suggest that pan-Arctic ice extent in summer is the lowest it has been in at least the past 1,450 years.[147] Winter ice extent has declined less than summer ice extent (see Ch. 2: Our Changing Climate, Key Message 11), indicative of a trend toward seasonal-only (as opposed to year-round) ice cover, which is relatively thin and vulnerable to melt in the summer. Recent work has indicated that the loss of summer sea ice may be affecting the atmospheric circulation in autumn and early winter. For example, there are indications that a weakening of subpolar westerly winds during autumn is an atmospheric response to a warming of the lower troposphere of the Arctic.[148] Extreme summer ice retreat also appears to be increasing the persistence of associated mid-latitude weather patterns, which may lead to an increased prob-

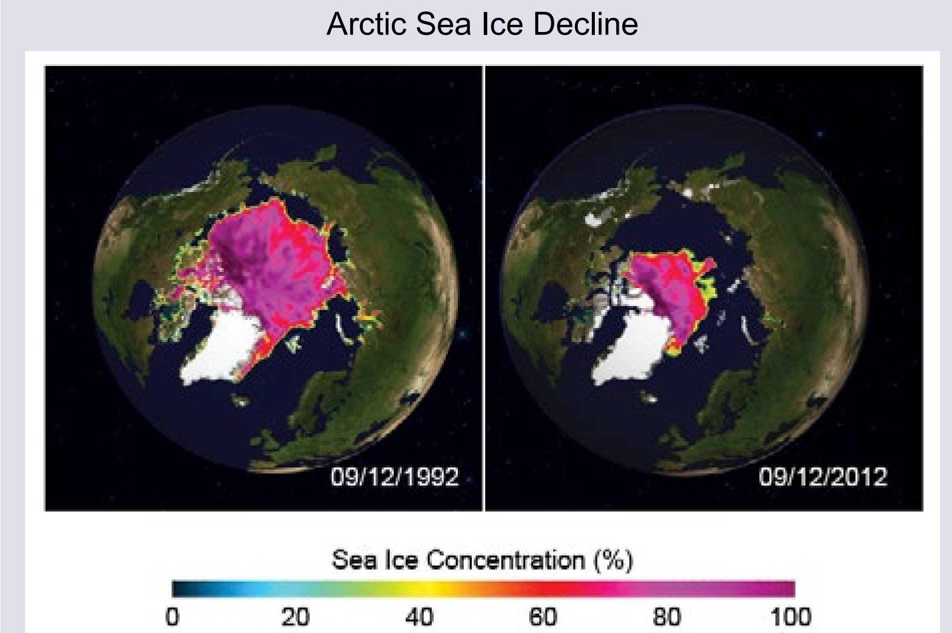


Figure 37. The spatial extent of Arctic sea ice cover in September has decreased substantially in the past two decades, as shown in this pair of satellite images depicting sea ice concentrations. The reduction of September sea ice extent from 1992 (left) to 2012 (right) has been nearly 50%, or about 1.2 million square miles (3 million square kilometers), which is nearly one-third the area of the contiguous United States. (Figure source: University of Illinois, The Cryosphere Today;[150] Data from the National Snow and Ice Data Center).

ability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves.[149] However, the combination of interannual variability and the small sample of years with extreme ice retreat make it difficult to identify a geographically consistent atmospheric response pattern in the middle latitudes.

On land, changes in permafrost provide compelling indicators of a warming climate, as they tend to reflect long-term average changes in climate. Borehole measurements are particularly useful, as they provide information from levels below about 10-meter depth where the seasonal cycle becomes negligible. Increases in borehole temperatures over the past several decades are apparent at various locations, including Alaska, northern Canada, Greenland, and northern Russia. The increases are about 3.6°F at the two stations in northern Alaska (Deadhorse and West Dock). In northern Alaska and northern Siberia, where permafrost is cold and deep, thaw of the entire permafrost layer is not imminent. However, in the large areas of discontinuous permafrost of Russia, Alaska, and Canada, average annual temperatures are sufficiently close to freezing that permafrost thaw is a risk within this century. Thawing of permafrost can release methane into the atmosphere, amplifying warming (see Supplemental Message 5), as well as potentially causing infrastructure and environmental damages.

There is evidence that the active layer (the near-surface layer of seasonal thaw, typically up to three feet deep) may be thickening in many areas of permafrost, including in northern Russia and Canada.[152] Permafrost thaw in coastal areas increases the vulnerability of coastlines to erosion by ocean waves, which in turn are exacerbated by the loss of sea ice from coastal areas affected by storms.

Increased melt is reducing both the mass and areal extent of glaciers over much of the Northern Hemisphere. Over the past decade, the contribution to sea level rise from glaciers and small ice caps (excluding Greenland) has been comparable to the contributions from the Greenland Ice Sheet.[153]

Projections of future mass loss by glaciers and small ice caps indicate a continuation of current trends, although these projections are based only on the changes in temperature and precipitation projected by global climate models; they do not include the effects of dynamical changes (for example, glacier movement). While there is a wide range among the projections derived from different global climate models, the models are consistent in indicating that the effects of melting will outweigh the effects of increases in snowfall. The regions from which the contributions to sea level rise are projected to be largest are the Canadian Arctic, Alaska, and the Russian Arctic.[151]

Permafrost Temperatures Rising

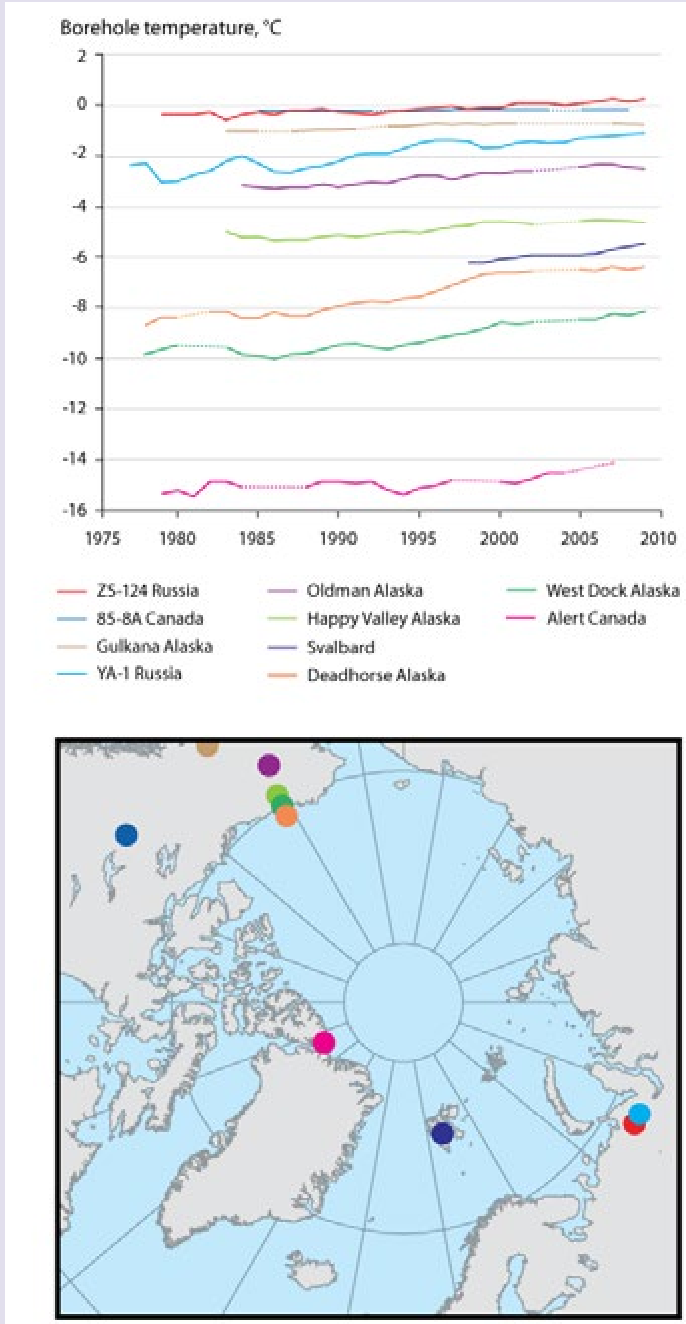


Figure 38. Ground temperatures at depths between 33 and 66 feet (10 and 20 meters) for boreholes across the circumpolar northern permafrost regions. Lower panel shows locations of measurement sites in colors corresponding to lines in upper panel (Figure source: AMAP 2011[151]).

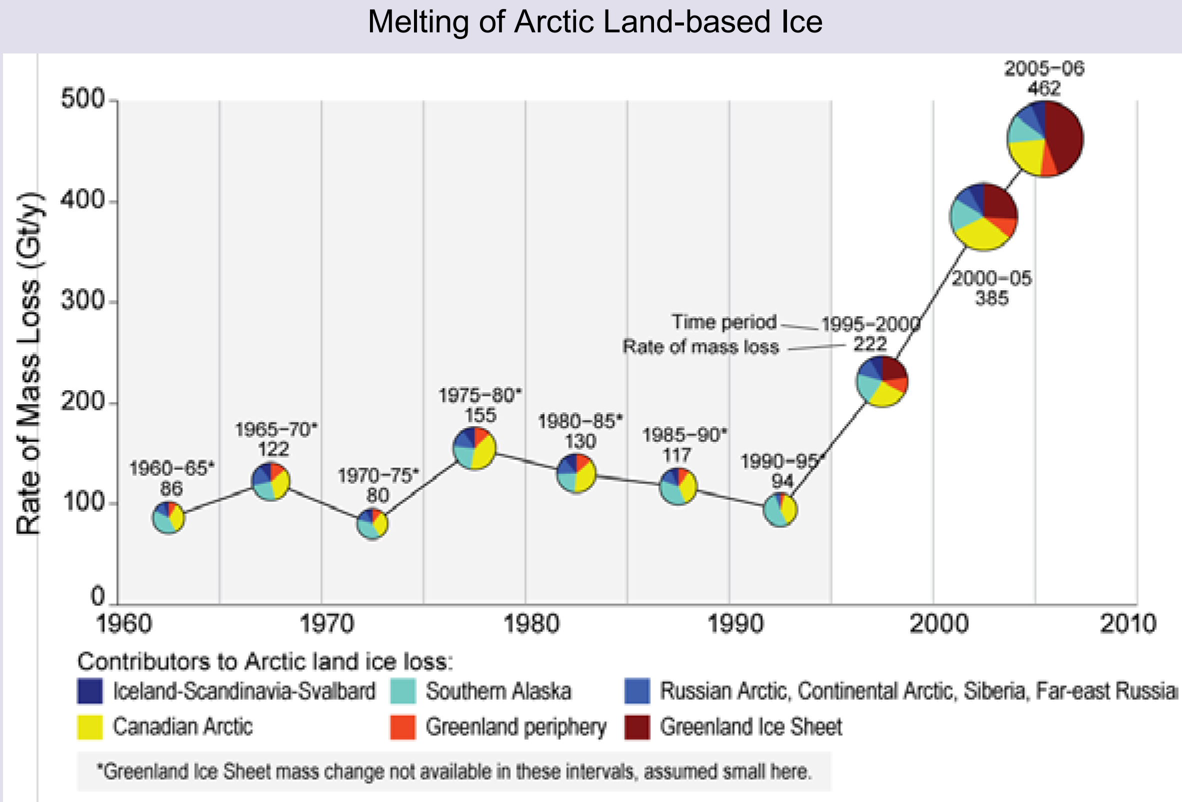


Figure 39. Inputs of freshwater to the ocean from mountain glaciers, small ice caps, and the Greenland Ice Sheet have increased dramatically in the past two decades. The size of the circles in the figure is proportional to the five-year average freshwater contributions to the ocean from melting of land-based ice. The coloring indicates the relative contributions from the Greenland Ice Sheet (brown) and mountain glaciers from the Greenland periphery (orange), Iceland-Scandinavia-Svalbard (dark blue), the Canadian Arctic (yellow), southern Alaska (light blue), and the Russian Arctic (medium blue). The largest contributions from mountain glaciers have been from the Canadian Arctic and southern Alaska. Note that contributions from mass changes of the Greenland Ice Sheet are not available prior to the mid-1990s, but they are assumed to have been small during this earlier period because annual snow accumulation was in approximate balance with annual meltwater discharge. (Figure source: AMAP 2011[151]).

On the left is a photograph of Muir Glacier in Alaska taken on August 13, 1941; on the right, a photograph taken from the same vantage point on August 31, 2004. Total glacial mass has declined sharply around the globe, adding to sea level rise. (Left photo by glaciologist William O, Field; right photo by geologist Bruce F. Molnia of the United State Geological Survey.)

Melting Glaciers Lead to Sea Level Rise

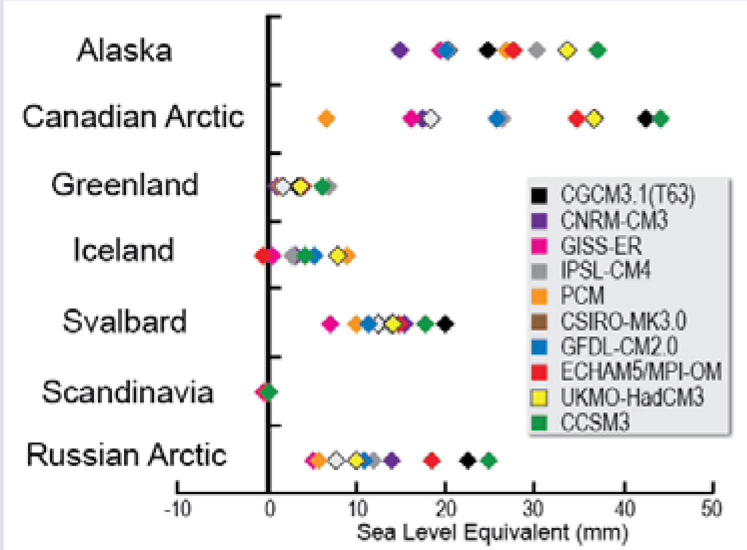


Figure 40. Projections of contributions to sea level rise by 2100 for seven regions that include all Arctic glaciers. Projections are based on temperature and precipitation simulated by ten different global climate models from CMIP3. For each region, the estimates are shown in different colors corresponding to the ten different models. (Figure source: adapted from Radić and Hock 2011[154]).

Supplemental Message 12.

Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

The rising global average sea level is one of the hallmarks of a warming planet. It will also be one of the major impacts of human-caused global warming on both human society and the natural environment.

Global sea level is increasing as a result of two different processes. First, the oceans absorb more than 90% of the excess heat trapped by human interference with the climate system, and this warms the oceans.[155] Like mercury in a thermometer, the warmer ocean water expands, contributing to global sea level rise. Second, the warmer climate also causes melting of glaciers and ice sheets. This meltwater eventually runs off into the ocean and contributes to sea level rise as well. A recent synthesis of surface and satellite measurements of the ice sheets shows that the rate at which the Greenland and Antarctic ice sheets contribute to sea level rise has been increasing rapidly and has averaged 0.02 inches (plus or minus 0.008) per year since 1992, with Greenland's contribution being more than double that of Antarctica.[156] In addition, local sea level change can differ from the global average sea level rise due to changes in ocean currents, local land movement, and even changes in the gravitational pull of the ice sheets and changes in Earth's rotation.

There is high confidence that global sea level will continue to rise over this century and beyond and that most coastlines will see higher water levels. The rates of sea level rise along individual coastlines are difficult to predict, as they can vary depending on the region. For example, globally averaged sea level has risen steadily by about 2.4 inches over the past two decades. But during that time, many regions have seen much more rapid rise while some have experienced falling sea levels. These complicated patterns are caused by changes in ocean currents and movement of heat within the oceans. Many of these patterns are due in part to natural, cyclic changes in the oceans. On the West Coast of the United States, sea level has fallen slightly since the early 1990s. Recent work suggests that a natural cycle known as the Pacific Decadal Oscillation has counteracted most or all of the global sea level signal there. This means that in coming decades the West Coast is likely to see faster than average sea level rise as this natural cycle changes phase.[157]

Along any given coastline, determining the rate of sea level rise is complicated by the fact that the land may be rising or sinking. Along the Gulf Coast, for example, local geological factors including extraction of oil, natural gas, and water from under-ground reservoirs are causing the land to sink, which could increase the effect of global sea level rise by several inches by the end of this century.[158] In some other locations, coastlines are rising as they continue to rebound from glaciation during the last glacial maximum. Predicting the future of any single coastline requires intimate knowledge of the local geology as well as the processes that cause sea levels to change at both the local and global scale.

Greenland and Antarctica hold enough ice to raise global sea levels by more than 200 feet if they were to melt completely. While this is very unlikely over at least the next few centuries, studies suggest that meltwater from ice sheets could contribute anywhere from several inches to 4.5 feet to global sea levels by the end of this century.[159] Because their behavior in a warming climate is still very difficult to predict, these two ice sheets are the biggest wildcards for potential sea level rise in the coming decades. What is certain is that these ice sheets are already responding to the warming of the oceans and the atmosphere. Satellites that measure small changes in the gravitational pull of these two regions have proven that both Greenland and Antarctica are currently losing ice and contributing to global sea level rise.[160]

In the United States, an estimated 5 million people currently live within 4 feet of current high tide lines, which places them at increasing risk of flooding in the coming decades.[161] Although sea level rise is often thought of as causing a slow inundation, the most immediate impacts of sea level rise are increases in high tides and storm surges. A recent assessment of flood risks in the United States found that the odds of experiencing a "100-year flood" are on track to double by 2030.

Sea Level Rise, 1993-2012

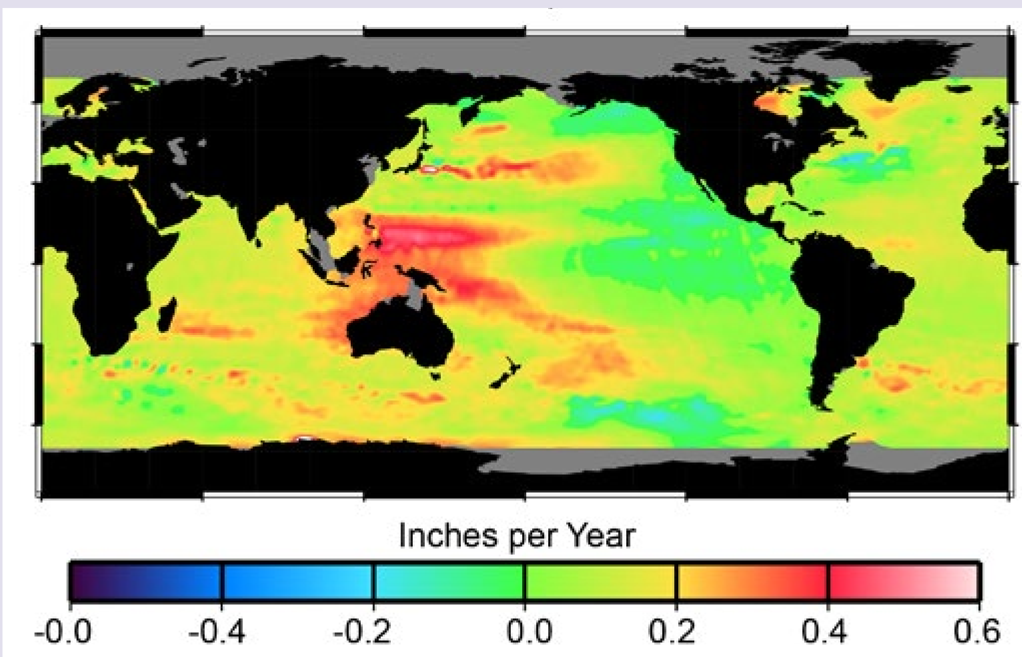


Figure 41. The patterns of sea level rise between 1993 and 2012 as measured by satellites. The complicated patterns are a reminder that sea levels do not rise uniformly.[162] (Figure source: University of Colorado, Sea Level Research Group).

Ice Loss from Greenland and Antarctica

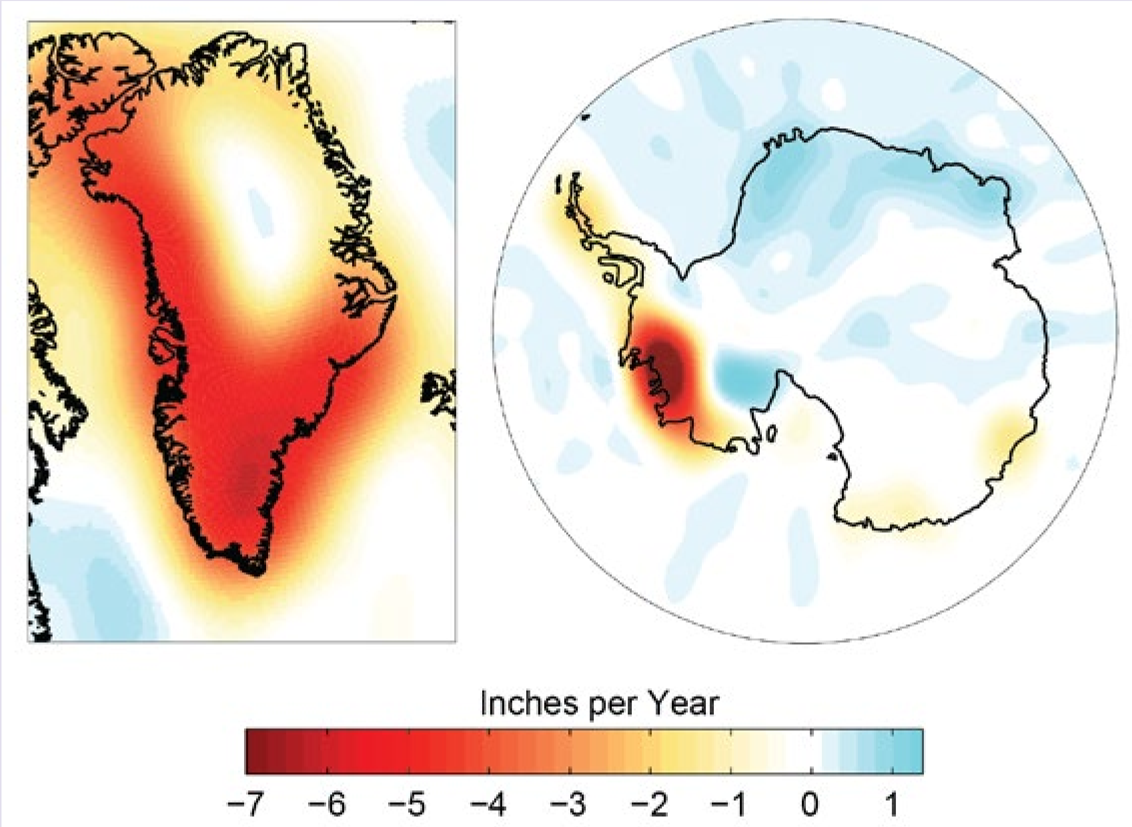


Figure 42. Rate of local ice sheet mass loss (in inches of water-equivalent-height per year) from Greenland (left) and Antarctica (right) from 2003 to 2012. The GRACE (Gravity Recovery and Climate Experiment) satellites measure changes in the pull of gravity over these two regions. As they lose ice to the oceans, the gravitational pull of Greenland and Antarctica is reduced. Analyses of GRACE data have now proven that both of the major ice sheets are currently contributing to global sea level rise due to ice loss. Over the periods plotted here, Greenland lost enough ice to raise sea level at a rate of 0.028 inches per year (0.72 mm/yr), and Antarctica lost ice at a rate that caused 0.0091 inches of sea level rise per year (0.24 mm/yr). (Figure source: NASA Jet Propulsion Laboratory, (left) updated from Velicogna and Wahr 2013;[163] (right) updated from Ivins et al. 2013[164]).

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APPENDIX 4
FREQUENTLY ASKED QUESTIONS

Convening Lead Authors

John Walsh, University of Alaska Fairbanks

Donald Wuebbles, University of Illinois

Lead Authors

Katharine Hayhoe, Texas Tech University

James Kossin, NOAA National Climatic Data Center

Kenneth Kunkel, CICS-NC, North Carolina State Univ., NOAA National Climatic Data Center

Graeme Stephens, NASA Jet Propulsion Laboratory

Peter Thorne, Nansen Environmental and Remote Sensing Center

Russell Vose, NOAA National Climatic Data Center

Michael Wehner, Lawrence Berkeley National Laboratory

Josh Willis, NASA Jet Propulsion Laboratory

Contributing Authors

David Anderson, NOAA National Climatic Data Center

Viatcheslav Kharin, Canadian Centre for Climate Modelling and Analysis, Environment Canada

Thomas Knutson, NOAA Geophysical Fluid Dynamics Laboratory

Felix Landerer, NASA Jet Propulsion Laboratory

Tim Lenton, Exeter University

John Kennedy, UK Meteorological Office

Richard Somerville, Scripps Institution of Oceanography, Univ. of California, San Diego

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On the Web: http://nca2014.globalchange.gov/report/appendices/faqs

FAQ INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

APPENDIX 4 FREQUENTLY ASKED QUESTIONS

This section answers some frequently asked questions about climate change. The questions addressed range from those purely related to the science of climate change to those that extend to some of the issues being faced in consideration of mitigation and adaptation measures. The author team selected these questions based on those often asked in presentations to the public. The answers are based on peer-reviewed science and assessments and have been confirmed by multiple analyses.

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

B. Is the climate changing? How do we know?

C. Climate is always changing. How is recent change different than in the past?

D. Is the globally averaged surface temperature still increasing? Isn't there recent evidence that it is actually cooling?

E. Is it getting warmer at the same rate everywhere? Will the warming continue?

F. How long have scientists been investigating human influences on climate?

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

H. Could the sun or other natural factors explain the observed warming of the past 50 years?

I. How do we know that human activities are the primary cause of recent climate change?

J. What is and is not debated among climate scientists about climate change?

K. Is the global surface temperature record good enough to determine whether climate is changing?

L. Is Antarctica gaining or losing ice? What about Greenland?

M. Weren't there predictions of global cooling in the 1970s?

N. How is climate projected to change in the future?

O. Does climate change affect severe weather?

P. How are the oceans affected by climate change?

Q. What is ocean acidification?

R. How reliable are the computer models of the Earth's climate?

S. What are the key uncertainties about climate change?

T. Are there tipping points in the climate system?

U. How is climate change affecting society?

V. Are there benefits to warming?

W. Are some people more vulnerable than others?

X. Are there ways to reduce climate change?

Y. Are there advantages to acting sooner rather than later?

Z. Can we reverse global warming?

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

Predicting how climate will change in future decades is a different scientific issue from predicting weather a few weeks from now. Weather is short term and chaotic, largely determined by whatever atmospheric system is moving through at the time, and thus it is increasingly difficult to predict day-to-day changes beyond about two weeks into the future. Climate, on the other hand, is a long-term statistical average of weather and is determined by larger-scale forces, such as the level of heat-trapping gases in the atmosphere and the energy coming from the sun. Thus it is actually easier to project how climate will change in the future. By analogy, while it is impossible to predict the age of death of any individual, the average age of death of an American can be calculated. 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 life expectancy of the average American who smokes. We can predict that on average, a smoker will not live as long as a non-smoker. Similarly, we can project what the climate will be like if we emit less heat-trapping gas, and what it will be like if we emit more.

Weather is the day-to-day variations in temperature, precipitation, and other aspects of the atmosphere around us. Weather prediction using state-of-the-art computer models can be very accurate for a few days to more than a week in advance. Because weather forecasts are based on the initial conditions of the atmosphere and ocean at the time the prediction is made, accuracy decays over time. After about two weeks, the effects of small errors in defining these initial conditions grow so large that meteorologists can no longer discern what the weather will be like on any specific day or place.

Climate is long-term average weather – the statistics of weather over long time scales, typically of 30 years or more. Climate is primarily the result of the effects of local geography, such as distance from the equator, distance from the ocean, and local topography and elevation, combined with larger scale climate factors that can change over time. These include the amount of energy from the sun and the composition of the atmosphere, including the amount of greenhouse gases and tiny particles suspended in the atmosphere. Knowing all these factors enables scientists to quantify the climate at a given place and time. Climate change occurs when these large-scale climate factors change over time.

Using our understanding of the physics of how the atmosphere works, we can estimate how climate will change in the future – in response to human activities, which are now changing Earth's atmospheric composition faster than at any time in at least the last 800,000 years. It is also possible to estimate changes in the statistics of certain types of weather events, such as heat waves or heavy precipitation events, especially when we know what is causing them to change.

We know how climate has changed in the recent past, and often we know why those changes have occurred. For example, the increase in global temperature, or global warming, that has occurred over the last 150 years can only be explained if we include the impact of increasing levels of heat-trapping gases in the atmosphere caused by human activities. The present generation of climate models can successfully reproduce the past warming and therefore provide an essential tool to peer into the future.

The role of human activities in driving recent change is discussed in FAQ I. (In the context of a changing climate, the term "human activities" is used throughout these frequently asked questions to refer specifically to activities, such as extracting and burning fossil fuels, deforestation, agriculture, waste treatment, and so on, that produce heat-trapping gases like carbon dioxide, methane, and nitrous oxide and/or emissions of black carbon, sulfate, and other particles.) Other human activities, like changes in land use, can also alter climate, especially on local or regional scales, such as that which occurs with urban heat islands.

U.S. Annual Average Temperature

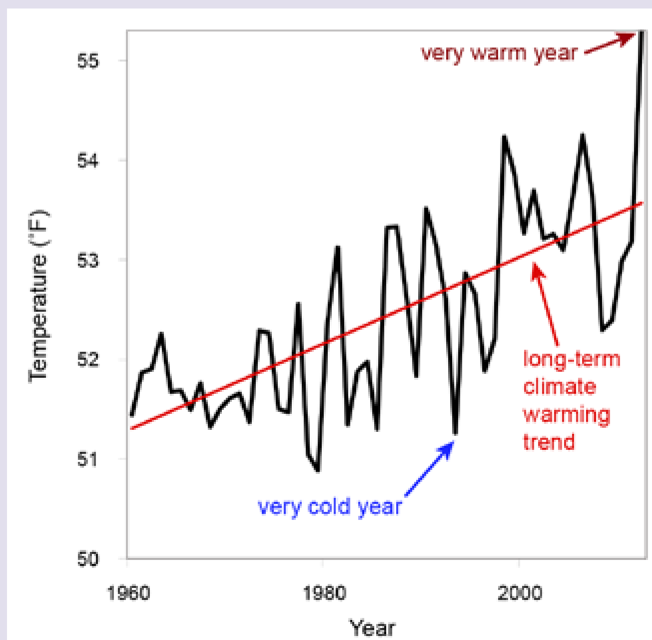

Figure 1. Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. Year-to-year and even decade-to-decade conditions do not necessarily tell us much about long-term changes in climate. One cold year, or even a few cold years in a row, does not contradict a long-term warming trend, even as one hot year does not prove it. (Figure source: adapted from Kunkel et al. 2013[1]).

B. Is the climate changing? How do we know?

Yes. The world has warmed over the last 150 years, and that warming has triggered many other changes to the Earth's climate. Evidence for a changing climate abounds, from the top of the atmosphere to the depths of the oceans. Changes in surface, atmospheric, and oceanic temperatures; melting glaciers, snow cover, and sea ice; rising sea level; and increase in atmospheric water vapor have been documented by hundreds of studies conducted by thousands of scientists around the world. Rainfall patterns and storms are changing and the occurrence of droughts is shifting.

Documenting climate change often begins with global average temperatures recorded near Earth's surface, where people live. But these temperatures, recorded by weather stations, are only one indicator of climate change. Additional evidence for a warming world comes from a wide range of consistent measurements of the Earth's climate system. It is the sum total of these indicators that lead to the conclusion that warming of our planet is unequivocal.

Evidence for a changing climate is not confined to the Earth's surface. Measurements by weather balloons and satellites consistently show that the temperature of the troposphere – the lowest layer of the atmosphere – has increased. The temperature of the upper atmosphere, particularly the stratosphere, has cooled, consistent with expectations of changes due to increasing concentrations of CO_2 and other greenhouse gases. The upper ocean has warmed, and more than 90% of the additional energy absorbed by the climate system since the 1960s has been stored in the oceans. As the oceans warm, seawater expands, causing sea level to rise.

As the troposphere warms, Arctic ice and glaciers melt, also causing sea level to rise. About 90% of the glaciers and land-based ice sheets worldwide are melting as the Earth warms, adding further to the sea level rise. Spring snow cover has decreased across the Northern Hemisphere since the 1950s. There have been substantial losses in sea ice in the Arctic Ocean, particularly at the end of summer when sea ice extent is at a minimum (see FAQ L for discussion of Antarctic sea ice).

Warmer air, on average, contains more water vapor. Globally, the amount of water vapor in the atmosphere has increased over the land and the oceans over the last half century. In turn, many parts of the planet have seen increases in heavy rainfall events. All of these indicators and all of the independent data sets for each indicator unequivocally point to the same conclusion: from the ocean depths to the top of the troposphere, the world has warmed and the climate has reacted to that warming.

Ten Indicators of a Warming World

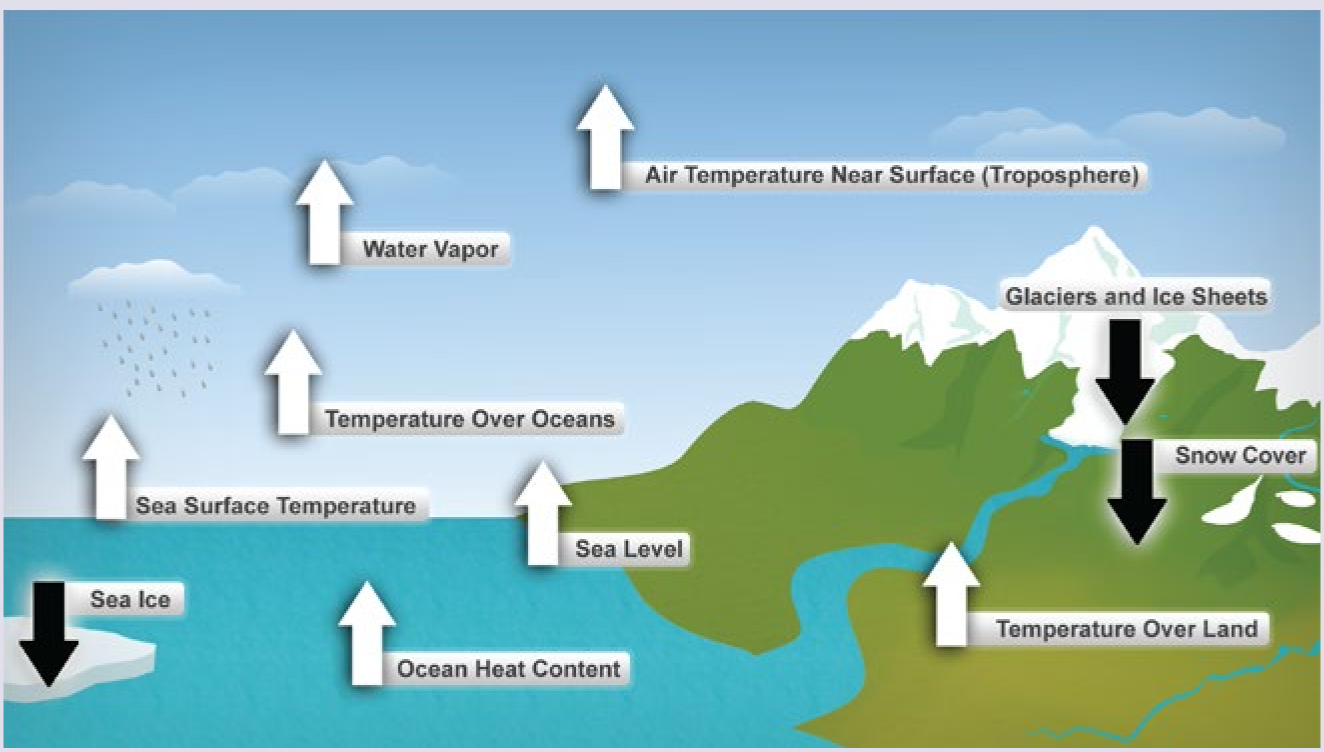

Figure 2. These are just some of the many indicators measured globally over many decades that demonstrate that the Earth's climate is warming. White arrows indicate increases, and black arrows show decreases. All the indicators expected to increase in a warming world are increasing, and all those expected to decrease in a warming world are decreasing. See Figure 3 for measurements showing these trends. (Figure source: NOAA NCDC; based on data updated from Kennedy et al. 2010[2]).

In summary, the evidence that climate is changing comes from a multitude of independent observations. The evidence that climate is changing because of human activity, as discussed in FAQ I and in more detail in Chapter 2: Our Changing Climate and Appendix 3: Climate Science Supplement, comes from observations, basic physics, and analyses from modeling studies.

Indicators of Warming from Multiple Data Sets

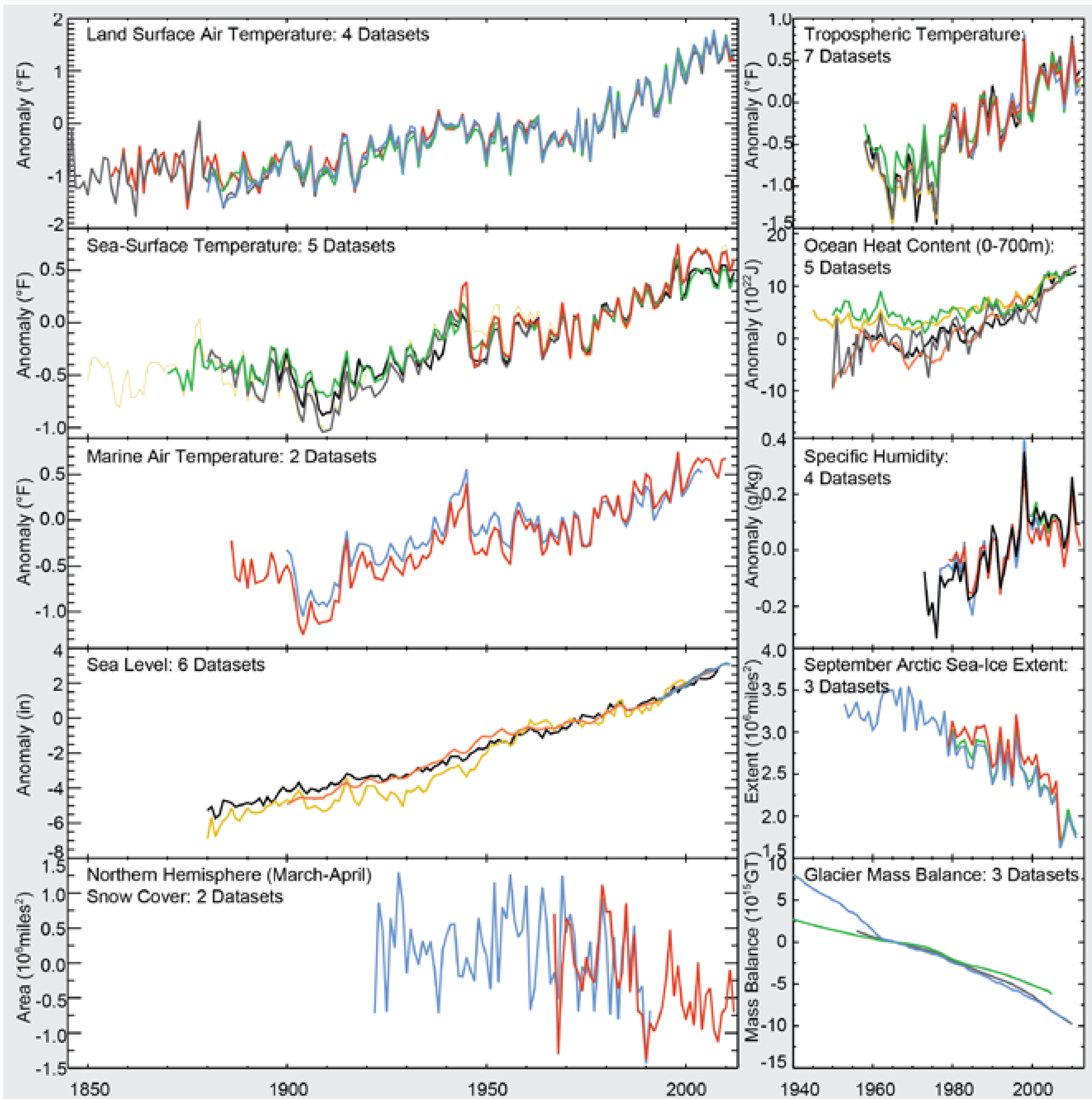

Figure 3. This figure summarizes some of the many datasets documenting changes in the Earth's climate, all of which are consistent with a warming planet. In all figures except the lower two in the right column, data are plotted relative to averages over the period 1960-1999 (Figure source: updated from Kennedy et al. 2010[2]).

C. Climate is always changing. How is recent change different than in the past?

The Earth has experienced many large climate changes in the past. However, current changes in climate are unusual for two reasons: first, many lines of evidence demonstrate that these changes are primarily the result of human activities (see Question I for more info); and second, these changes are occurring (and are projected to continue to occur) faster than many past changes in the Earth's climate.

In the past, climate change was driven exclusively by natural factors: explosive volcanic eruptions that injected reflective particles into the upper atmosphere, changes in energy from the sun, periodic variations in the Earth's orbit, natural cycles that transfer heat between the ocean and the atmosphere, and slowly changing natural variations in heat-trapping gases in the atmosphere. All of these natural factors, and their interactions with each other, have altered global average temperature over periods ranging from months to thousands of years. For example, past glacial periods were initiated by shifts in the Earth's orbit, and then amplified by resulting decreases in atmospheric levels of carbon dioxide and subsequently by greater reflection of solar radiation by ice and snow as the Earth's climate system responded to a cooler climate. Some periods in the distant past were even warmer than what is expected to occur from human-induced global warming. But these changes in the distant past generally occurred much more slowly than current changes.

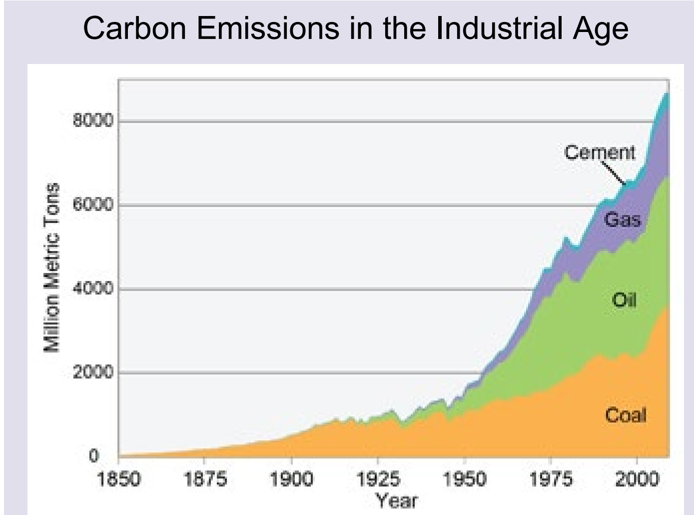

Figure 4. Global carbon emissions from burning coal, oil, and gas and from producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades. (Data from Boden et al. 2012[3]).

Natural factors are still affecting the planet's climate today. The difference is that, since the beginning of the Industrial Revolution, humans have been increasingly affecting global climate, to the point where we are now the primary cause of recent and projected future change.

Records from ice cores, tree rings, soil boreholes, and other forms of "natural thermometers," or "proxy" climate data, show that recent climate change is unusually rapid compared to past changes. After a glacial maximum, the Earth typically warms by about 7°F to 13°F over thousands of years (with periods of rapid warming alternating with periods of slower warming, and even cooling, during that time). 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.

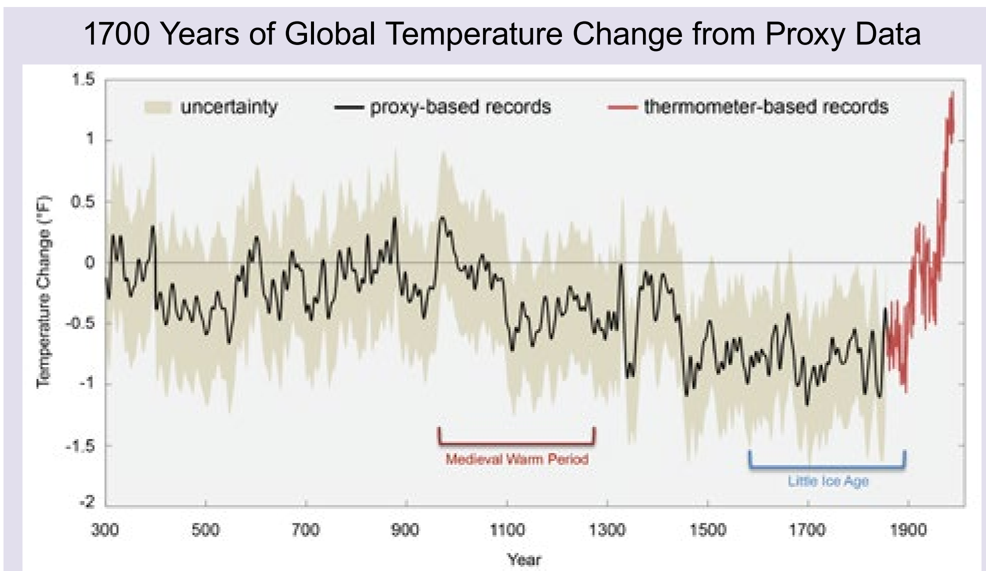

Figure 5. Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[4]).

Global temperatures over the last 100 years are unusually high when compared to temperatures over the last several thousand years. Atmospheric carbon dioxide levels are currently higher than any time in at least the last 800,000 years. Paleoclimate studies indicate that temperature and atmospheric carbon dioxide levels have been higher in the distant past, millions of years ago, when the world was very different than it is today. But never before have such rapid, global-scale changes occurred during the history of human civilization.

Our societies have not been built to withstand the changes that are anticipated in the relatively near future, and thus are not prepared for the effects they are already experiencing: higher temperatures, sea level rise, and other climate change related impacts.

D. Is the globally averaged surface air temperature still increasing? Isn't there recent evidence that it is actually cooling?

Global temperatures are still rising. Climate change is defined as a change in the average conditions over periods of 30 years or more (see FAQ A). On these time scales, global temperature continues to increase. Over shorter time scales, natural variability (due to the effects of El Niño and La Niña events in the Pacific Ocean, for example, or volcanic eruptions or changes in energy from the sun) can reduce the rate of warming or even create a temporary reduction in average surface air temperature. These short-term variations in no way negate the reality of long-term warming. The most recent decade was the warmest since instrumental record keeping began around 1880.

From 1970 to 2010, for example, global temperature trends taken at five-year intervals show both decreases and sharp increases. The five-year period from 2005 to 2010, for example, included a period in which the sun's output was at a low point, oceans took up more than average amounts of heat, and a series of small volcanoes exerted a cooling influence by adding small particles to the atmosphere. These natural factors are thought to have contributed to a recent slowdown in the rate of increase in average surface air temperature caused by the buildup of human-induced greenhouse gases. But while there has been a slowdown in the rate of increase, temperatures are still increasing.

Short-term Variations Versus Long-term Trend

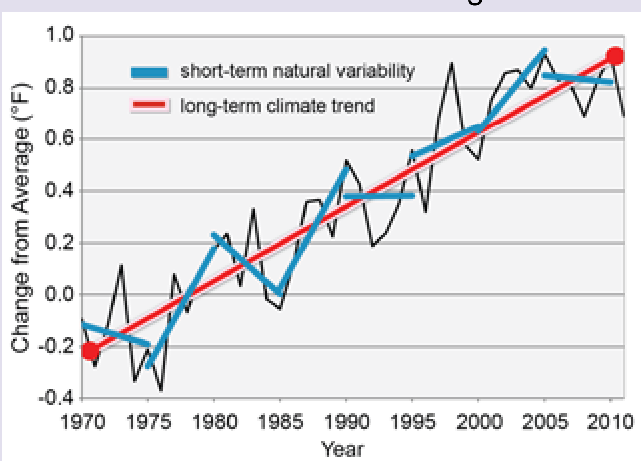

Figure 6. Short-term trends in global temperature (blue lines show temperature trends at five-year intervals from 1970 to 2010) can range from decreases to sharp increases. The evidence of climate change is based on long-term trends over 20-30 years or more (red line). (Data from NOAA NCDC).

In addition, satellite and ocean observations indicate that most of the increased energy in the Earth's climate system from the increasing levels of heat-trapping gases has gone into the oceans. These observations indicate that the Earth-atmosphere climate system has continued to gain heat energy.

In the United States, there has been considerable decade-to-decade variability superimposed on the long-term warming trend. In most seasons and regions, the 1930s were relatively warm and the 1960s/1970s relatively cool. The most recent decade of the 2000s was the warmest on record throughout the United States and globally.

Global Temperature Change: Decade Averages

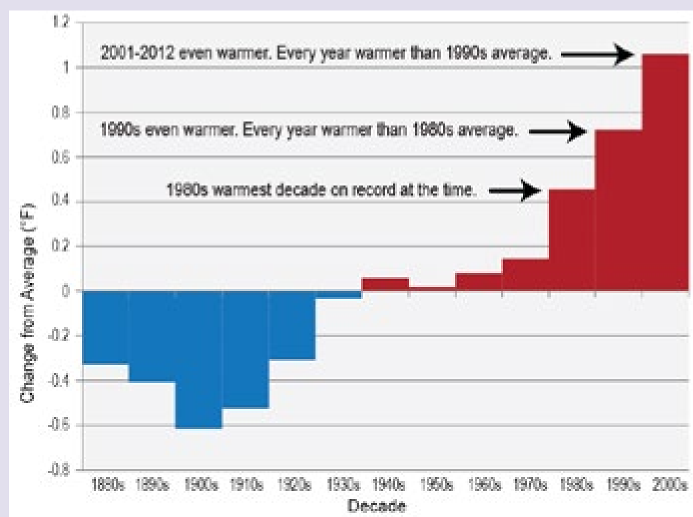

Figure 7. The last five decades have seen a progressive rise in Earth's average surface temperature. Bars show the difference between each decade's average temperature and the overall average for 1901 to 2000. The far right bar includes data for 2001-2012. (Figure source: NOAA NCDC).

E. Is it getting warmer at the same rate everywhere? Will the warming continue?

Temperatures are not increasing at the same rate everywhere, because temperature changes in a given location depend on many factors. However, average global temperatures are projected to continue increasing throughout the remainder of this century due to heat-trapping gas emissions from human activities.

The planet is warming overall (see FAQ I), but some locations could be cooling due to local factors. Temperature changes in a given location are a function of multiple factors, including global and local forces, and both human and natural influences. In some places, including the U.S. Southeast, temperatures actually declined over the last century as a whole (although they have risen in recent decades). Possible causes of the observed lack of warming in the Southeast during the 20th century include increased cloud cover and precipitation,[5] increases in the presence of fine particles called aerosols in the atmosphere (including those produced by burning fossil fuels and by natural sources), expanding forests in the Southeast over this period,[6] decreases in the amount of heat conducted from land to the atmosphere as a result of increases in irrigation,[7] and multi-decadal variability in sea surface temperatures in both the North Atlantic[8] and the tropical Pacific[9] Oceans. At smaller geographic scales, and during certain time intervals, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale. An observed decrease in temperature at an individual location does not negate the fact that, overall, the planet is warming.

In terms of impacts, "global warming" is probably not the most immediate thing most people would notice. A changing climate affects our lives in many more obvious ways, for example, by increasing the risk of severe weather events such as heat waves, heavy precipitation events, strong hurricanes, and many other aspects of climate discussed throughout this report.

For these reasons, many scientists prefer the term "climate change," which connotes a much larger picture: broad changes in what are considered "normal" conditions. This term encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and other features of the climate system.

At the global scale, some future years will be cooler than the preceding year; some decades could even be cooler than the preceding decade (though that has not happened for more than six decades; see Figure 7). Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future. Nonetheless, each successive decade in the last 30 years has been the warmest in the period of reliable instrumental records (going back to 1850). Based on this historical record and plausible scenarios for future increases in heat-trapping gases, we expect that future global temperatures, averaged over climate timescales of 30 years or more, will be higher than preceding periods as a result of carbon dioxide and other heat-trapping gas emis-

Temperature Trends, 1900-2012

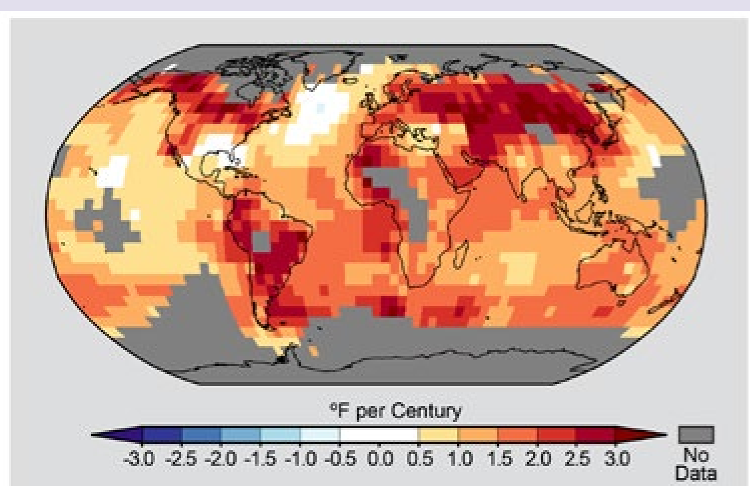

Figure 8. Observed trend in temperature from 1900 to 2012; yellow to red indicates warming, while shades of blue indicate cooling. Gray indicates areas for which there are no data. There are substantial regional variations in trends across the planet, though the overall trend is warming. (Figure source: NOAA NCDC).

Decade-Scale Changes in Average Temperature for U.S. Regions

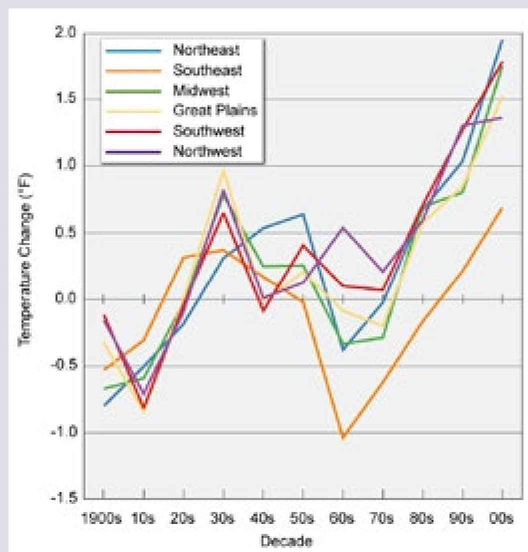

Figure 9. Change in decadal-averaged annual temperature relative to the 1901-1960 average for the six National Climate Assessment regions in the contiguous United States. This figure shows how regional temperatures can be much more variable than global temperatures, going up and down from decade to decade; all regions, however, show warming over the last two decades or more. In the figure, 00s refers to the 12-year period of 2001-2012. (Figure source: NOAA NCDC / CICS-NC).

sions from human activities. A portion of the carbon dioxide emissions from human activities will remain in the atmosphere for hundreds of years and continue to affect the global carbon cycle for thousands of years. Year-to-year projections of regional and local temperatures are more variable than global temperatures, and even at a particular location, future warming becomes increasingly likely over longer periods of time.[1]

F. How long have scientists been investigating human influences on climate?

The scientific basis for understanding how heat-trapping gases affect the Earth's climate dates back to the French scientist Joseph Fourier, who established the existence of the natural greenhouse effect in 1824. The heat-trapping abilities of greenhouse gases were corroborated by Irish scientist John Tyndall with experiments beginning in 1859. Since then, scientists have developed more tools to refine their understanding of human influences on climate, from the invention of the thermometer, to the development of computerized climate models, to the launching of Earth observing satellites that, together, provide global data coverage.

The greenhouse effect is caused by heat-trapping gases, such as water vapor, carbon dioxide, and methane, in the Earth's atmosphere. These gases are virtually transparent to the visible and ultraviolet wavelengths that comprise most of the sun's energy, allowing nearly all of it to reach Earth's surface. However, they are relatively opaque to the heat energy the Earth radiates back outward at infrared wavelengths. Other more abundant gases in the atmosphere like nitrogen and oxygen are largely transparent to the Earth's infrared energy. Greenhouse gases trap some of the Earth's energy inside the atmosphere and prevent it from escaping to space by absorbing and re-emitting that energy in all directions, rather than just upwards. Some of the trapped energy is re-radiated back down to the Earth's surface. This natural trapping effect makes the average temperature of the Earth nearly 60°F warmer than what it would be otherwise. On other planets, like Venus, where there are much higher concentrations of heat-trapping gases in the atmosphere, the greenhouse effect has a much stronger influence on surface temperature, making conditions far too hot for life as we know it.

By the late 1800s, scientists were aware that burning coal, oil, or natural gas produced carbon dioxide, a key heat-trapping gas. They were also aware that methane, another heat-trapping gas, was released during coal mining and other human activities. And they knew that, since the Industrial Revolution, humans were producing increasing amounts of these gases. It was clear that humans were increasing the natural greenhouse effect and that this would warm the planet.

In 1890, Svante Arrhenius, a Swedish chemist, calculated the effect of increasing fossil fuel use on global temperature. This climate model, computed by hand, took two years to complete. Arrhenius' results were remarkably similar to those produced by the most up-to-date global climate models today, although he did not anticipate that atmospheric levels of carbon dioxide would increase as quickly as they have.

In 1938, a British engineer, Guy Callendar, connected rising carbon dioxide levels to the observed increase in the Earth's temperature that had occurred to date. In 1958, Charles David Keeling began to precisely measure atmospheric levels of carbon dioxide in the relatively unpolluted location of Mauna Loa on Hawai'i. Today, those data provide a clear record of the effect of human activities on the chemical composition of the global atmosphere. Many more sources of data corroborate the work of these early pioneers in the field of climate science.

Early Scientists who Established the Scientific Basis for Climate Change

Figure 10. Scientists whose research was key to understanding the greenhouse effect and the impact of human activities on climate.

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

The reason heat-trapping gases like carbon dioxide, methane, and nitrous oxide have such a powerful influence on Earth's climate is their potency: although they are transparent to visible and ultraviolet solar energy, allowing the sun's energy to come in, they are very strong absorbers of the Earth's infrared heat energy, blanketing the Earth and preventing some of the energy to escape to space.

Before the Industrial Revolution, natural levels of carbon dioxide in the atmosphere averaged around 280 parts per million (ppm), that is, 280 molecules of CO_2 per million molecules of air (which is mostly nitrogen and oxygen). In other words, carbon dioxide made up about 0.028% of the volume of the atmosphere. Methane and nitrous oxide, other heat-trapping gases, made up even less, about 700 parts per billion (ppb) and 270 ppb, respectively. Over the last few centuries, emissions from human activities have increased carbon dioxide levels to about 400 ppm, or more than 3,000 billion tons – more than a 40% increase. Over the same time period, methane and nitrous oxide levels in the atmosphere have risen to around 1800 ppb and 320 ppb, respectively.

As the concentrations in the atmosphere of these heat-trapping gases increase due to human activities, they are absorbing greater and greater amounts of infrared heat energy emitted from the Earth's surface. As discussed in FAQ F, the gases then re-radiate some of this heat back to the surface, effectively trapping the heat inside the Earth's climate system and warming the Earth's surface.

These heat-trapping gases do not absorb energy equally across the infrared spectrum. Carbon dioxide absorption is very strong at certain wavelengths of infrared radiation, whereas water vapor absorbs more broadly across most of the spectrum. Water vapor is the most important naturally occurring heat-trapping greenhouse gas, but small increases in heat energy absorption by carbon dioxide and other heat-trapping gases trigger increases in water vapor that amplify the infrared trapping, leading to further warming. As a result, water vapor is considered a "feedback" rather than a direct forcing on climate.

Human Influence on the Greenhouse Effect

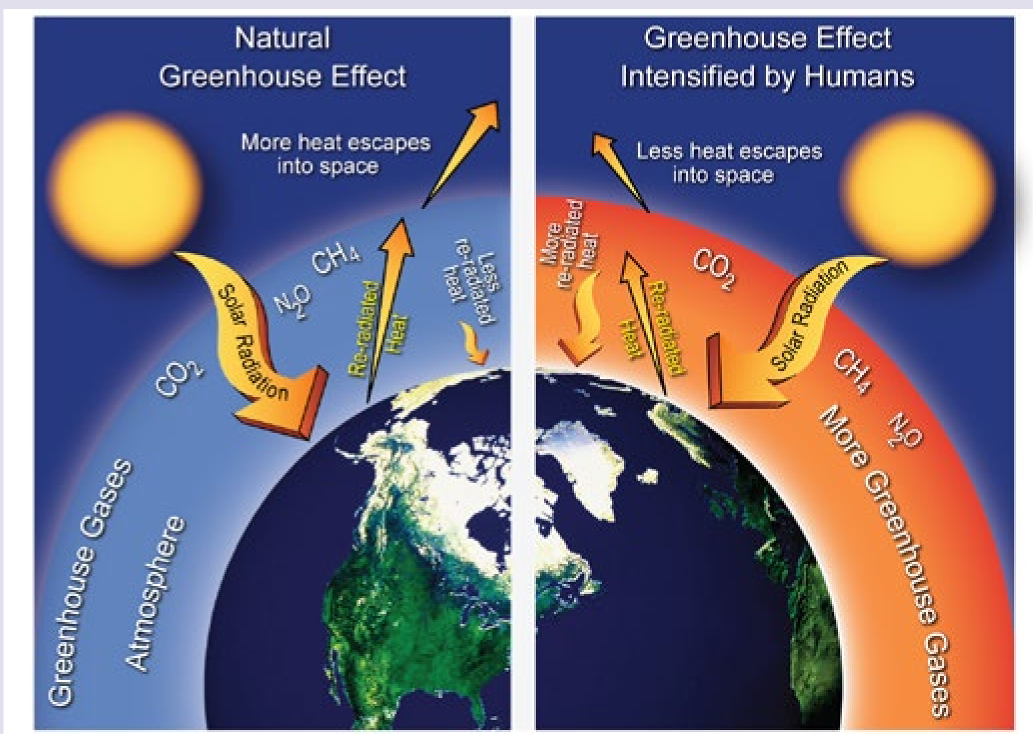

Figure 11. (left) A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. (right) In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service[10]).

H. Could the sun or other natural factors explain the observed warming of the past 50 years?

No. Since accurate satellite-based measurements of solar output began in 1978, the amount of the sun's energy reaching Earth has slightly decreased, which should, on its own, result in slightly lower temperatures; but the Earth's temperature has continued to rise. The sun can explain less than 10% of the increase in temperature since 1750, and none of the increase in temperature since 1960.

Patterns of vertical temperature change (from the Earth's surface to the upper atmosphere) provide further evidence that the sun cannot be responsible for the observed changes in climate. An increase in solar output would warm the atmosphere consistently from top to bottom. Warming from increasing heat-trapping gases, on the other hand, should be concentrated in the lower atmosphere (troposphere), while the upper atmosphere (stratosphere) would cool. Satellite measurements and weather balloon records reveal that the troposphere has warmed, and the stratosphere has cooled. This observed pattern of vertical temperature change matches what we would expect from the increase in heat-trapping gases, not an increase in solar output.

Changes in the sun's magnetic field are known to affect the intensity of cosmic rays reaching Earth's atmosphere and there is some suggestion that this could affect cloud formation; however, observations indicate that the magnitude of this effect is much smaller than the effects from the human-related changes in heat-trapping gases and from particle emissions on clouds and the changes in climate.

Large explosive volcanic eruptions can cool climate for a few years after an eruption, if the eruption is powerful enough to send particles far up into the atmosphere. In the atmosphere, sulfur dioxide from volcanoes is converted into sulfuric acid particles that can scatter sunlight, cooling the Earth's surface. Particles from exceptionally large eruptions like Mount Pinatubo in 1991 or Krakatoa in 1883 can reach all the way into the stratosphere, where they can stay for several years. Eventually, they fall back into the troposphere where they are rapidly removed by precipitation. Volcanoes also emit carbon dioxide, but this amount is less than 1% annually of the emissions occurring from human activities.

Thus, natural factors cannot explain recent warming. In fact, observed solar and volcanic activity would have tended to slightly cool the Earth, and other natural variations are too small to account for the amount of warming over the last 50 years.

Measurements of Surface Temperature and Sun's Energy

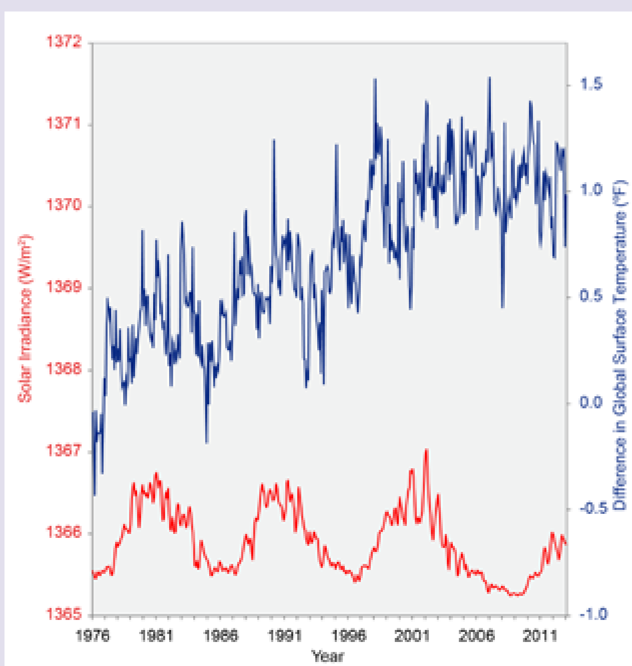

Figure 12. Changes in the global surface temperature (top) and the solar flux (bottom) since 1900 (temperatures are relative to 1961-1990). The temperatures are based on thermometer observations of the Earth's surface temperature, while the solar flux at the top of Earth's atmosphere is based on satellite observations starting in 1978 and on proxy observations before then. (Figure source: NOAA NCDC / CICS-NC).

I. How do we know that human activities are the primary cause of recent climate change?

Many lines of evidence demonstrate that human activities are primarily responsible for recent climate changes. First, basic physics dictates that increasing the concentration of CO_2 and other heat-trapping gases in the atmosphere will cause the climate to warm. Second, modeling studies show that when human influences are removed from the equation, climate would actually have cooled slightly over the past half century. And third, the pattern of warming through the layers of atmosphere demonstrates that human-induced heat-trapping gases are responsible, rather than some natural change.

Scientists are continually designing experiments to test whether observed climate changes are unusual and then to determine their causes. This field of study is known as "detection and attribution." Detection involves looking for evidence of changes or trends. Attribution attempts to identify the causes of these changes from a line-up of "suspects" that include changes in energy from the sun, powerful volcanic eruptions – and today, human-induced emissions of heat-trapping gases.

Detection and attribution analyses have confirmed that recent changes cannot have been caused either by internal climate system variations or by solar and volcanic influences (see FAQs C and H). Human influences on the climate system – including heat-trapping gas emissions, atmospheric particulates, and land-use and land-cover change – are required to explain recent changes (see Figure 14).

Detection and attribution has been used to analyze the contribution of human influences to changes in global average conditions, in extreme events, and even in the change in risk of specific types of events, such as the 2003 European heat wave. Such analyses have found that it is virtually certain that observed changes in many aspects of the climate system are the result of influences of human activities. Scientific analyses also provide extensive evidence that the likelihood of some types of extreme events (such as heavy rains and heat waves) is now significantly higher due to human-induced climate change.

Human Influences Apparent in Many Aspects of the Changing Climate

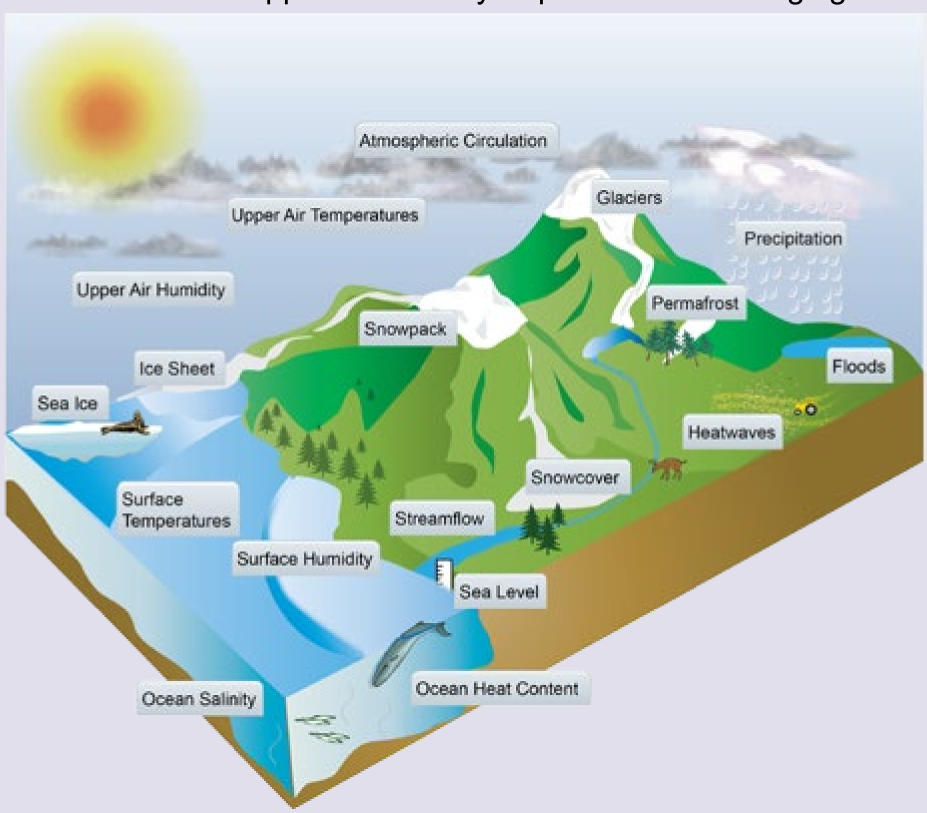

Figure 13. Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

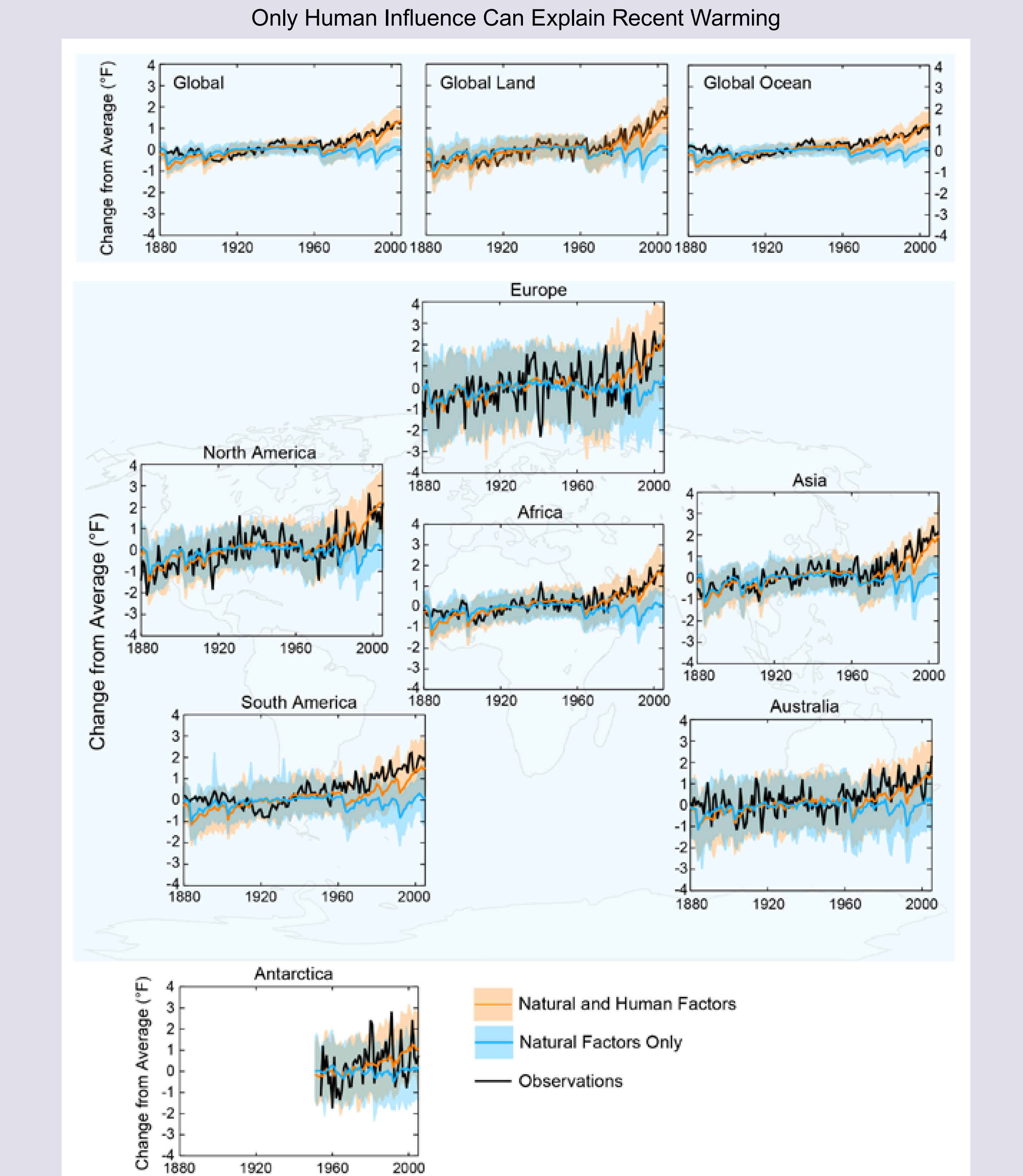

Figure 14. Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading represents estimates from a broad range of climate simulations including solely natural (solar and volcanic) changes in forcing. The orange shading is from climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013[11]).

J. What is and is not debated among climate scientists about climate change?

Multiple analyses of the peer-reviewed science literature have repeatedly shown that more than 97% of scientists in this field agree that the world is unequivocally warming and that human activity is the primary cause of the warming experienced over the past 50 years. Spirited debates on some details of climate science continue, but these fundamental conclusions are not in dispute.

The scientific method is built on scrutiny and debate among scientists. Scientists are rigorously trained to conduct experiments to test a question, or hypothesis, and submit their findings to the scrutiny of other experts in their field. Part of that scrutiny, known as "peer review," includes independent scientists examining the data, analysis methods, and findings of a study that has been submitted for publication. This peer review process provides quality assurance for scientific results, ensuring that anything published in a scientific journal has been reviewed and approved by other independent experts in the field and that the authors of the original study have adequately responded to any criticisms or questions they received.

However, peer review is only the first step in the long process of acceptance of new ideas. After publication, other scientists will often undertake new studies that may support or reject the findings of the original study. Only after an exhaustive series of studies over many years, by many different research groups, are new ideas widely accepted.

Given that new scientific understanding emerges from this exhaustive process, the widespread agreement in the scientific community regarding the reality of climate change and the leading role of human activities in driving this change is striking. This consensus includes agreement on the fundamental scientific principles that underlie this phenomenon, as well as the weight of empirical evidence that has been accumulated over decades, and even centuries, of research (see FAQ F).

The conclusion that the world is warming, and that this is primarily due to human activity, is based on multiple lines of evidence, from basic physics to the patterns of change through the climate system (including the atmosphere, oceans, land, biosphere, and cryosphere). The warming of global climate and its causes are not matters of opinion; they are matters of scientific evidence, and that evidence is clear. Scientists do not "believe" in human-induced climate change; rather, the widespread agreement among scientists is based on the vast array of evidence that has accumulated over the last 200 years. When all of the evidence is considered, the conclusions are clear.

There is more work to be done to fully understand the many complex and interacting aspects of climate change, and important questions remain. Scientific debate continues on questions such as: Exactly how sensitive is the Earth's climate to human emissions of heat-trapping gases? How will climate change affect clouds? How will climate change affect snowstorms in Chicago, tornadoes in Oklahoma, and droughts in California? How do particle and soot emissions affect clouds? How will climate change be affected by changes in clouds and the oceans? These detailed questions, and more, serve as healthy indicators that the scientific method is alive and well in the field of climate science. But the fact that climate is changing, that this is primarily in response to human activities, and that climate will continue to change in response to these activities, is not in dispute (see FAQ I).

Separating Human and Natural Influences on Climate

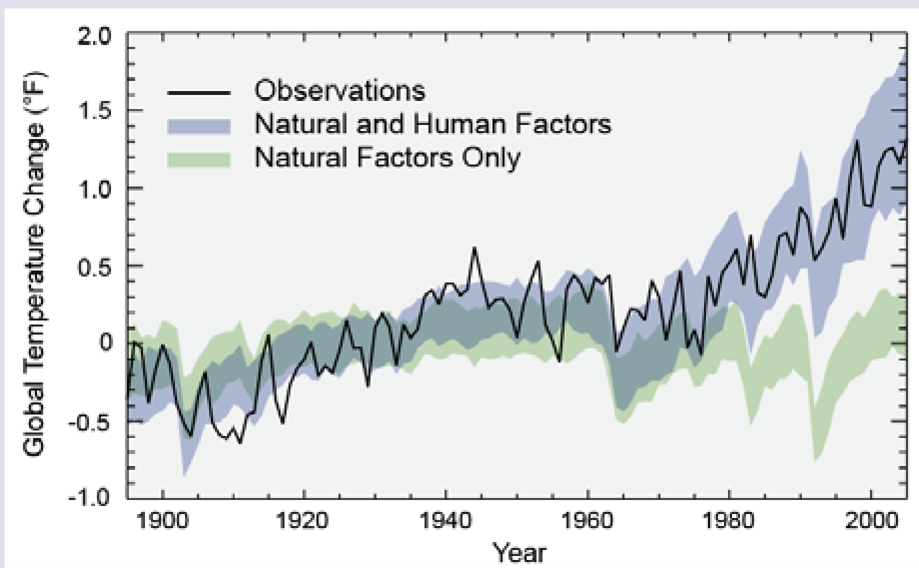

Figure 15. The green band shows how global average temperature would have changed due to natural forces only, as simulated by climate models. The blue band shows model simulations of the effects of human and natural factors combined. The black line shows observed global average temperatures. As indicated by the green band, without human influences, temperature over the past century would actually have cooled slightly over recent decades. The match up of the blue band and the black line illustrate that only the inclusion of human factors can explain the recent warming. (Figure source: adapted from Huber and Knutti, 2012[12]).

K. Is the global surface temperature record good enough to determine whether climate is changing?

Yes. There have been a number of studies that have examined the U.S. and global temperature records in great detail. These have used a variety of methods to study the effects of changes in instruments, time of observations, station siting, and other potential sources of error. All studies reinforce high confidence in the reality of the observed upward trends in temperature.

Global surface temperatures are measured by weather stations over land and by ships and buoys over the ocean. These records extend back regionally for over 300 years in some locations and near-globally to the late 1800s.

Scientists have undertaken painstaking efforts to obtain, digitize, and collate these records. Because of the way these measurements have been taken, many of the records contain results that are skewed by, for example, a change of instrument or a station move. It is essential to carefully examine the data to identify and adjust for such effects before the data can be used to evaluate climate trends.

A number of different research teams have taken up this challenge. Some have spent decades carefully analyzing the data and continually reassessing their approaches and refining their records. These independently produced estimates are in very good agreement at both global and regional scales.

Scientists have also considered other influences that could contaminate temperature records. For example, many thermometers are located in urban areas that could have warmed over time due to the urban heat island effect (in which heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside). At least three different research teams have examined how this might affect U.S. temperature trends. All have found that this effect is adequately accounted for by the data corrections. At the global scale, if all of the urban stations are removed from the global temperature record, the evidence of warming over the past 50 years remains intact. Other studies have shown that the temperature *trends* of rural and urban areas in close proximity essentially match, even though the urban areas may have higher temperatures overall.

Observed Change in Global Average Temperature

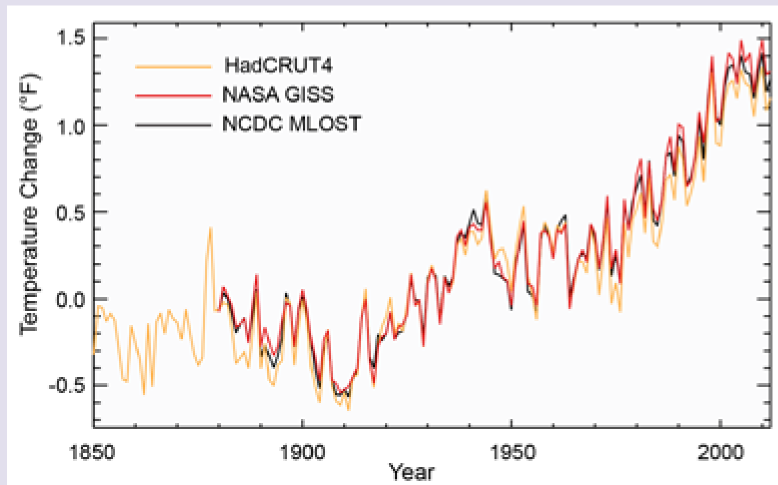

Figure 16. Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

L. Is Antarctica gaining or losing ice? What about Greenland?

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.

One way that scientists are evaluating ice loss is by observing changes in the gravitational fields over Greenland and Antarctica. Fluctuations in the pull of gravity over these major ice sheets reflect the loss of ice over time. Over the last decade, the GRACE (Gravity Recovery and Climate Experiment) satellites have measured changes in the gravitational pull of the continents and revealed that, on the whole, both Greenland and Antarctica are losing ice. It is clear that these ice sheets are already losing mass as a result of human-induced climate change, and the evidence suggests that Greenland and Antarctica are likely to continue to lose ice mass for centuries. How rapidly the Greenland and Antarctic Ice Sheets will melt as warming continues represents the largest uncertainty in projections of future sea level rise.

Paleoclimate records show that the giant ice sheets of Greenland and Antarctica (as well as others, such as the Laurentide Ice Sheet that covered much of North America during the last glacial maximum) have expanded and contracted as the Earth cooled or warmed in the past. As temperature increases and precipitation patterns shift in response to human-induced climate change, scientists expect the ice sheets of Greenland and

Ice Loss from the Two Polar Ice Sheets

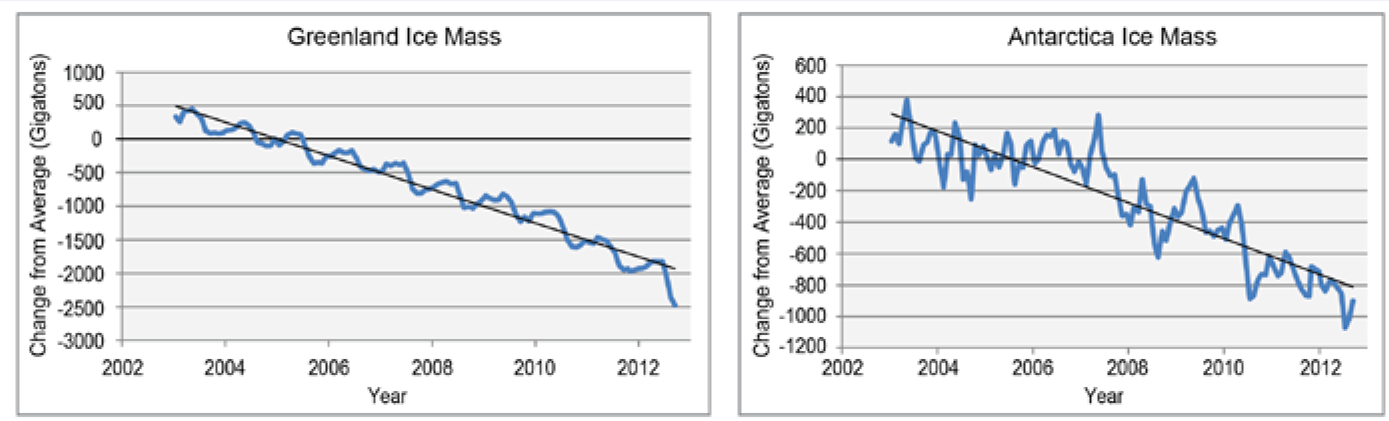

Figure 17. GRACE (Gravity Recovery and Climate Experiment) satellite measurements show that both Greenland and Antarctica are, on the whole, losing ice as the atmosphere and oceans warm. (Figure source: adapted from Wouters et al. 2013[13]).

Antarctica to continue responding in a similar way. Over time horizons of hundreds to thousands of years, a general melting and reduction in the extent of both of these ice sheets is expected to occur in response to global warming. Over shorter time frames of years to decades, however, the response of these ice sheets is more complicated.

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 melt of the ice sheet in the summer. However, the ice on the continent slowly flows down the mountains and through the valleys toward the ocean. Some parts of the ice sheet extend out into the ocean as "ice shelves." Here, above-freezing ocean water speeds up the process called "calving" that breaks the ice into free floating icebergs. Melting and calving and the flow of ice into the oceans around Antarctica has accelerated in recent decades and is now contributing about 0.005 to 0.010 inches per year to sea level rise. It is possible that the West Antarctic Ice Sheet, which contains enough ice to raise global sea levels by 10 feet, could begin to lose ice much more quickly if ice shelves in the region begin to disintegrate at the edges.

Greenland contains only about one tenth as much ice as the Antarctic Ice Sheet, but if Greenland's ice were to entirely melt, global sea level would rise 23 feet. Greenland is warmer than Antarctica, so unlike Antarctica, 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. Satellite measurements indicate that 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 causes the ice to flow toward the ocean. Several of the major outlet glaciers that drain the Greenland Ice Sheet have sped up in the past decade. Recent scientific studies suggest that warming of the ocean at the edges of the outlet glaciers may contribute to this speed-up. Greenland's ice loss has increased substantially in the past decade or two, and is now contributing 0.01 to 0.02 inches per year to sea level rise (about twice the rate of Antarctica's mass loss). This increased rate of ice loss means that Greenland's contribution to global sea level rise is now similar to the effect from smaller glaciers worldwide and from Antarctica.

M. Weren't there predictions of global cooling in the 1970s?

No. An enduring myth about climate science is that in the 1970s the climate science community supposedly predicted "global cooling" and an "imminent" ice age. A review of the scientific literature shows that this was not the case. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Where did all the discussion about global cooling come from? First, temperature records from about 1940 to 1970 showed a slight global cooling trend, intensified by temporary increases in snow and ice cover across the Northern Hemisphere. Short-term natural variations in the Earth's climate (see FAQ A) and increasing emissions of sulfur and other particles from coal-burning power plants, which reflect solar energy and have a net cooling effect on the Earth, likely contributed to cooler temperatures during that time period. Several unusually severe winters in Asia and parts of North America in the 1970s raised people's concerns about cold weather. The popular press, including *Time*, *Newsweek*, and *The New York Times*, carried a number of articles about cooling at that time.

Second, climate scientists study both natural and human-induced changes in climate. Over the last century, scientists have learned a great deal about what drives Earth's ice ages. Scientific understanding of what are called the Milankovitch cycles (cyclical changes in the Earth's orbit that can explain the onset and ending of ice ages) led a few scientists in the 1970s to suggest that the current warm interglacial period might be ending soon, plunging the Earth into a new ice age over the next few centuries. Scientists continue to study this issue today; the latest information suggests that, if the Earth's climate were 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 glaciation has now been delayed.

Published Climate Change Research Papers

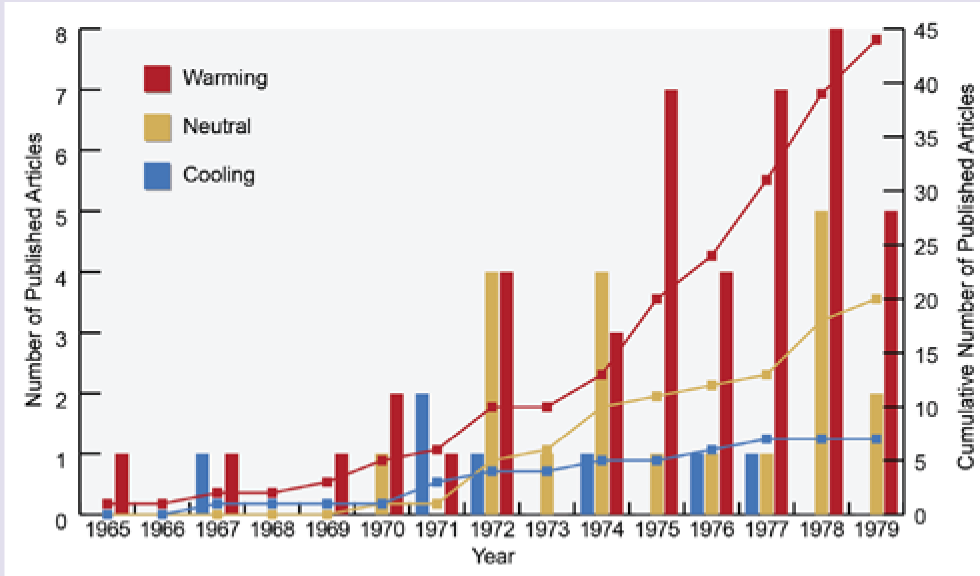

Figure 18. The number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories. Bars indicate number of articles published per year. Squares indicate cumulative number of articles published. For the period 1965 through 1979, the literature survey found seven papers suggesting further cooling, 20 neutral, and 44 warming. Even in the early years of the study of climate change, more science studies were discussing concerns about global warming than global cooling. (Figure source: Peterson et al. 2008[14]).

N. How is climate projected to change in the future?

Climate is projected to continue to warm, with the amount of future warming ranging from another 3°F to another 12°F by 2100, depending primarily on the level of emissions from human activities, principally the burning of fossil fuels. For precipitation, wet areas are generally projected to get wetter while dry areas get drier. More precipitation is expected to fall in heavy downpours. Natural variability will still play a role in year-to-year changes.

Future climate cannot be "predicted" because human activities are currently the most important driver of climate change and we cannot predict what society will choose to do with regard to emissions. Rather, we can *project* the climate change that would result from a given set of assumptions, or future scenarios, regarding human activities (including changes in population, technology, economics, energy, and policy). Future changes also have some uncertainty due to natural variability, particularly over shorter time scales (see FAQ A) and limitations in scientific understanding of exactly how the climate system will respond to human activities (see FAQ S).

The relative importance of these three sources of uncertainty changes over time. Which type of uncertainty is most important also depends on what type of change is being projected: whether, for example, it is for average conditions or extremes, or for temperature or precipitation trends (see FAQ S).

Over the next few decades, global average temperature over 30-year climate timescales is expected to continue to increase (see FAQ D), while natural variability still plays a significant role in year-to-year changes (see FAQ A). The amount of climate change expected over this time period is unlikely to be significantly altered by reducing current heat-trapping gas emissions alone or even by stabilizing atmospheric levels of carbon dioxide and other gases. This is because near-term warming will be caused primarily by emissions that have already occurred, due to the lag in the temperature response to changes in atmospheric composition. This lag is primarily the result of the very large heat storage capacity of the world's oceans and the length of time required for that heat to be transferred to the deep ocean. At smaller geographical scales, temperatures are projected to increase in most regions in the next few decades, but a few regions could experience flat or even decreasing temperatures. Any climate change always represents the net effect of multiple global and local factors, both human-related and natural (see FAQ E).

Beyond the middle of this century, global and regional temperature changes will be determined primarily by the rate and amount of various emissions released by human activities, as well as by the response of the Earth's climate system to those emissions. Efforts to rapidly and significantly reduce emissions of heat-trapping gases can still limit the global temperature increase to 3.6°F (2°C) relative to the 1901-1960 time period. However, significantly greater temperature increases are expected if emissions follow higher scenarios associated with continuing growth in the use of fossil fuels; in that case, the increase in U.S. average air temperature is likely to exceed 11°F by the end of this century. This amount of temperature increase would reshape human societies in ways that are almost unthinkable to us today.

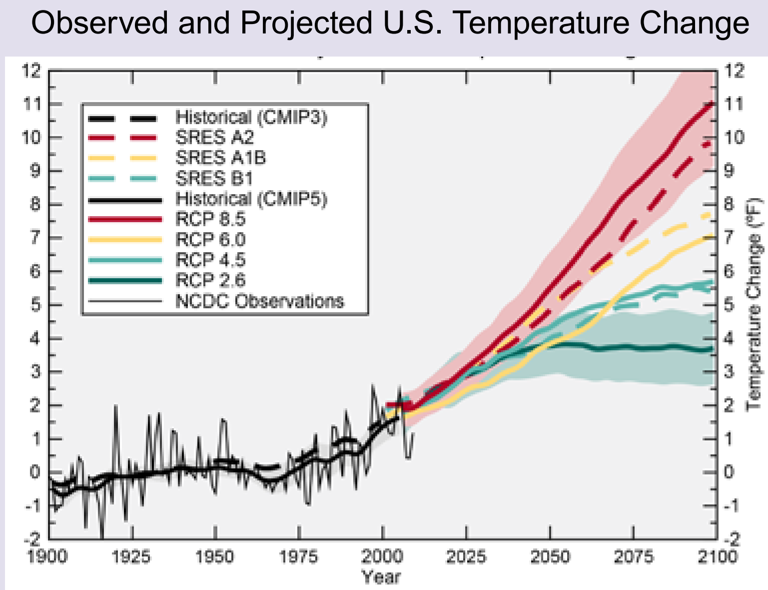

Figure 19. Projected average annual temperature changes over the contiguous United States for multiple future scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models and scenarios, while solid lines show the most recent generation of climate model simulations and scenarios. Changes in temperature over the U.S. are expected to be higher than the change in global average temperatures (Figure 23). Differences in these projections are principally a result of differences in the scenarios. (Data from CMIP3, CMIP5, and NOAA NCDC).

Precipitation patterns are also expected to continue to change throughout this century and beyond. In general, wet areas are projected to get wetter and dry areas, drier. In some areas, located in between wetter and drier areas, the total amount of precipitation falling over the course of a year is not expected to significantly change. Following the observed trends over recent decades, more precipitation is expected to fall as heavier precipitation events. In many mid-latitude regions, including the United States, there will be fewer days with precipitation but the wettest days will be wetter. Large-scale shifts towards wetter or drier conditions and the projected increases in heavy precipitation are expected to be greater under higher emissions scenarios as compared to lower ones.

O. Does climate change affect severe weather?

Yes, climate change can and has altered the risk of certain types of extreme weather events. The harmful effects of severe weather raise concerns about how the risk of such events might be altered by climate change. An unusually warm month, a major flood or a drought, a series of intense rainstorms, an active tornado season, landfall of a major hurricane, a big snowstorm, or an unusually severe winter inevitably lead to questions about possible connections to climate change.

For example, more extreme high temperatures and fewer extreme cold temperatures occur in a warmer climate (although extreme cold events can and do still occur – just less frequently). In the United States, more than twice as many high temperature records as compared to low temperature records were broken in the period of 2001-2012.

Also, in many areas, heavy rainfall events have already, and will continue to become more frequent and severe as climate continues to change. The intensity and rainfall rates of Atlantic hurricanes are projected to increase, with the strongest storms getting stronger. Recent research has shown how climate change can alter atmospheric circulation and weather patterns such as the jet stream, affecting the location, frequency, and duration of these and other extremes. While there have always been extreme events due to natural causes, scientific evidence indicates that the probability and severity of some types of events has increased due to climate change.

For other types of extreme weather events important to the United States, such as tornadoes and severe thunderstorms, more research is needed to understand how climate change will affect them. These events occur over much smaller scales, 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 with climate change, while others may decrease.

P. How are the oceans affected by climate change?

The oceans cover more than two-thirds of the Earth's surface and play a very important role in regulating the Earth's climate and in climate change. Today, the world's oceans absorb more than 90% of the heat trapped by increasing levels of carbon dioxide and other greenhouse gases in the atmosphere due to human activities. This extra energy warms the ocean, causing it to expand. This in turn causes sea level to rise. Of the global rise in sea level observed over the last 35 years, about 40% is due to this warming of the water. Most of the rest is due to the melting of glaciers and ice sheets. Ocean levels are projected to rise another 1 to 4 feet over this century, with the precise number largely depending on the amount of global temperature rise and polar ice sheet melt.

Observations from past climate combined with climate model projections of the future suggest that over the next 100 years the Atlantic Ocean's overturning circulation (known as the "Ocean Conveyor Belt") could slow down as a result of climate change. These ocean currents carry warm water northward across the equator in the Atlantic Ocean, warming the North Atlantic (and Europe) and cooling the South Atlantic. A slowdown of the Conveyor Belt would increase regional sea level rise along the east coast of the United States and change patterns of temperature in Europe and rainfall in Africa and the Americas, but would not lead to global cooling.

Warming ocean waters also affect marine ecosystems like coral reefs, which can be very sensitive to temperature changes. When water temperatures become too high, coral expel the algae (called zooxanthellae) which help nourish them and give them their vibrant color. This is known as coral bleaching. If the high temperatures persist, the coral die.

In addition to the warming, the acidity of seawater is increasing as a direct result of increasing atmospheric carbon dioxide (see FAQ Q). The oceans are now absorbing about a quarter of the carbon dioxide produced by human activities every year. The dissolved carbon dioxide reacts with seawater to form carbonic acid, which makes the water more acidic, making it more difficult for shellfish, corals, and other living things to grow their shells or skeletons. Both the increased acidity and higher temperature of the oceans are expected to negatively affect corals and other living things over the coming decades and beyond.

Coral Bleaching

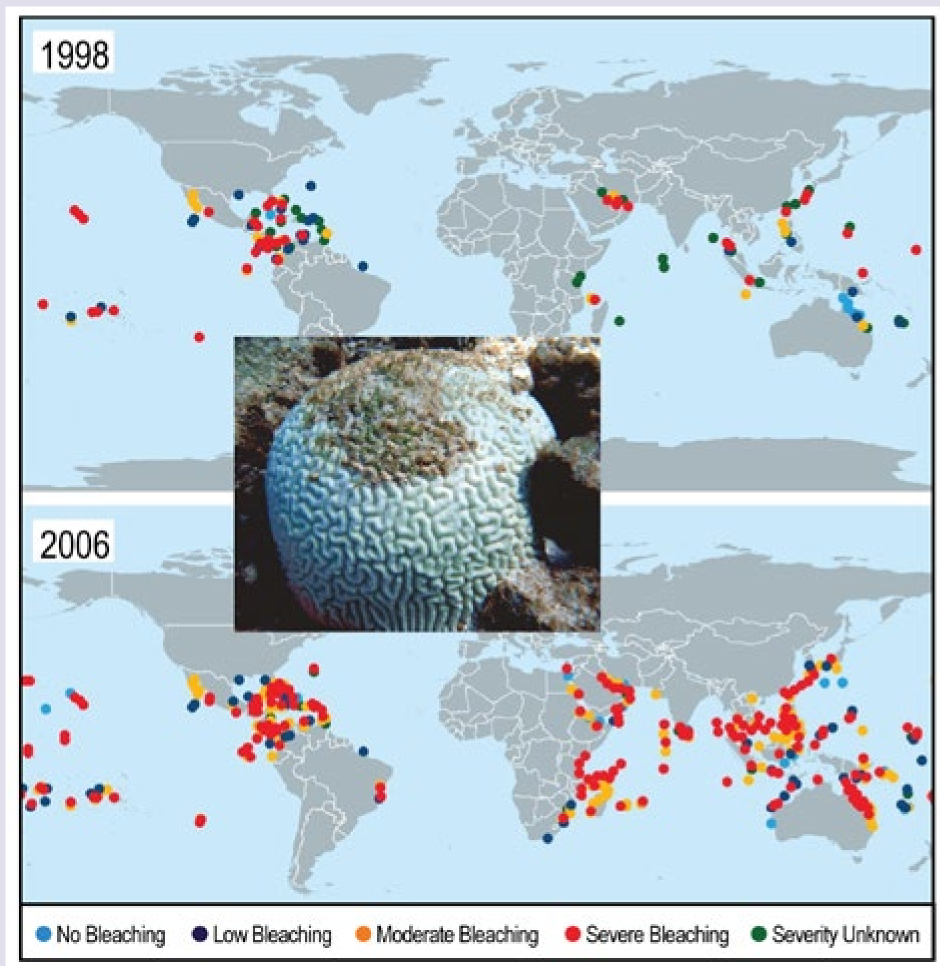

Figure 20. (Photo) Bleached brain coral; (Maps) The global extent and severity of mass coral bleaching have increased worldwide over the last decade. Red dots indicate severe bleaching. (Figure source: Marshall and Schuttenberg 2006;[15] Photo credit: NOAA).

Q. What is ocean acidification?

As human-induced emissions of carbon dioxide build up in the atmosphere, excess carbon dioxide dissolves into the oceans, where it reacts with seawater to form carbonic acid, which makes ocean waters more acidic and corrosive. These changes to ocean chemistry can affect many living things, and possibly the entire food web.

Dissolved calcium and carbonate ions are the building blocks for the skeletons and shells of many living things in the oceans. Ocean acidification lowers the availability of carbonate ions in many parts of the ocean, affecting the ability of some marine life to produce and maintain their shells.

Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units, representing approximately a 30% increase in acidity. The oceans will continue to absorb carbon dioxide produced by human activities and become even more acidic in the future. Projections of carbon dioxide levels indicate that by the end of this century the surface waters of the ocean could be as much as 150% more acidic, resulting in a pH that the oceans have not experienced for more than 20 million years and effectively transforming marine life as we know it.

Ocean acidification is expected to affect ocean species to varying degrees. Some photosynthetic algae and seagrass species may benefit from higher CO_2 conditions in the ocean, as they require CO_2 to live, as do plants on land. On the other hand, studies have shown that a more acidic environment has dramatic negative effects on some calcifying species, including pteropods, oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. When shelled species are at risk, the entire food web may also be at risk.

Ocean Acidification and the Food Web

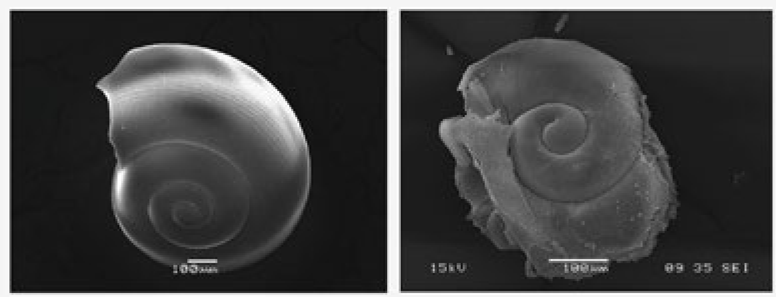

Figure 21. Pteropods, or "sea butterflies," are sea creatures about the size of a small pea. Pteropods are eaten by organisms ranging in size from tiny krill to whales, and are an important source of food for North Pacific juvenile salmon. The photos above show what happens to a pteropod's shell when it encounters seawater that is too acidic. The left panel shows a shell collected from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod collected in a region with higher acidity (Photo credits: (left) Bednaršek et al. 2012;[16] (right) Nina Bednaršek).

R. How reliable are the computer models of the Earth's climate?

Climate models are used to analyze past changes in the long-term averages and variations in temperature, precipitation, and other climate indicators, and to make projections of how these trends may change in the future. Today's climate models do a good job at reproducing the broad features of the present climate and changes in climate, including the significant warming that has occurred over the last 50 years. Hence, climate models can be useful tools for testing the effects of changes in the factors that drive changes in climate, including heat-trapping gases, particulates from human and volcanic sources, and solar variability.

Scientists have amassed a vast body of knowledge regarding the physical world. Unlike many areas of science, however, scientists who study the Earth's climate cannot build a "control Earth" and conduct experiments on this Earth in a lab. To experiment with the Earth, scientists instead use this accumulated knowledge to build climate models, or "virtual Earths." In studying climate change, these virtual Earths serve as an important way to integrate different kinds of knowledge of how the climate system works. These models can be used to test scientific understanding of the response of the Earth's climate to past changes (such as the transition from the last glacial maximum to our current warm interglacial period) as well as to develop projections of future changes (such as the response of the Earth's climate to human activities).

Climate models are based on mathematical and physical equations representing the fundamental laws of nature and the many processes that affect the Earth's climate system. When the atmosphere, land, and ocean are divided up into small grid cells and these equations are applied to each grid cell, the models can capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over longer timeframes, these models simulate wind patterns, high and low pressure systems, and other weather characteristics that make up climate.

Some important physical processes are represented by approximate relationships because the processes are not fully understood, or they are at a scale that a model cannot directly represent. Examples include clouds, convection, and turbulent mixing of the atmosphere, for which important processes are much smaller than the resolution of current models. These approximations lead to uncertainties in model simulations of climate.

Climate models require enormous computing resources, especially to capture the geographical details of climate. Today's most powerful supercomputers are enabling climate scientists to more thoroughly examine effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase another 100 fold or more, permitting even more details of the climate system to be explored.

Climate Models and Temperature Change

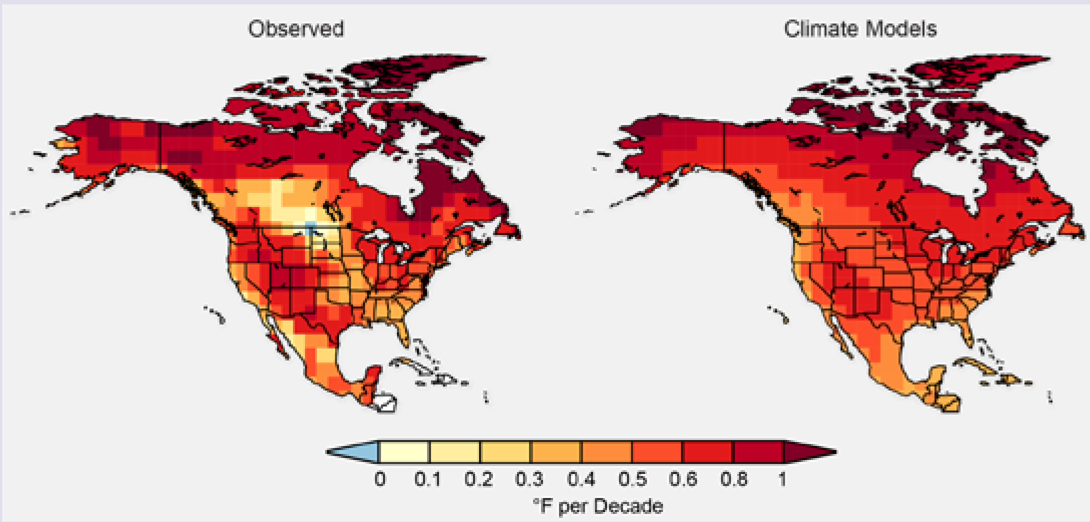

Figure 22. The large-scale geographical patterns and approximate magnitude of the surface air temperature trend from 1980 to 2005 from observational data (left) is approximately captured by computer models of the climate system (right). The pattern from the computer models is an average based on 43 different global climate models (CMIP5) used in the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report. The observations are a combination of both the human contribution to recent warming as well as the natural temperature variations. Averaging these model simulations suppresses the natural variations and thus shows mainly the human contribution, which is the reason that the smaller-scale details are different between the two maps. (Figure source: NOAA NCDC / CICS-NC).

S. What are the key uncertainties about climate change?

Available evidence gives scientists confidence that humans are having a significant effect on climate and will continue to do so over this century and beyond. In particular, continued use of fossil fuels and resulting emissions will significantly alter climate and lead to a much warmer world. Of course, it is impossible to predict the future with absolute certainty. The precise amount of future climate change that will occur over the rest of this century is uncertain for several reasons.

First, projections of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change as a result of population, energy, technology, and economics. Society may choose to reduce emissions or to continue to increase them. 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. And human choices are nearly impossible to predict.

A second source of uncertainty is natural variability, which affects climate over timescales from months to decades. These natural variations are largely unpredictable and are superimposed on the warming from increasing heat-trapping gases. Uncertainty in the sun's future output is another source of variability that is independent of human actions. Estimates of past changes in solar variability over the last several millennia suggest that the magnitude of solar effects over this century are likely to be small compared to the magnitude of the climate change effects projected from human activities.

A third source of uncertainty involves limitations to our current scientific knowledge. The Earth's climate system is complex, and continues to challenge scientists' understanding of exactly how it may respond to human influences. Observa-

Emissions Levels Determine Temperature Rises

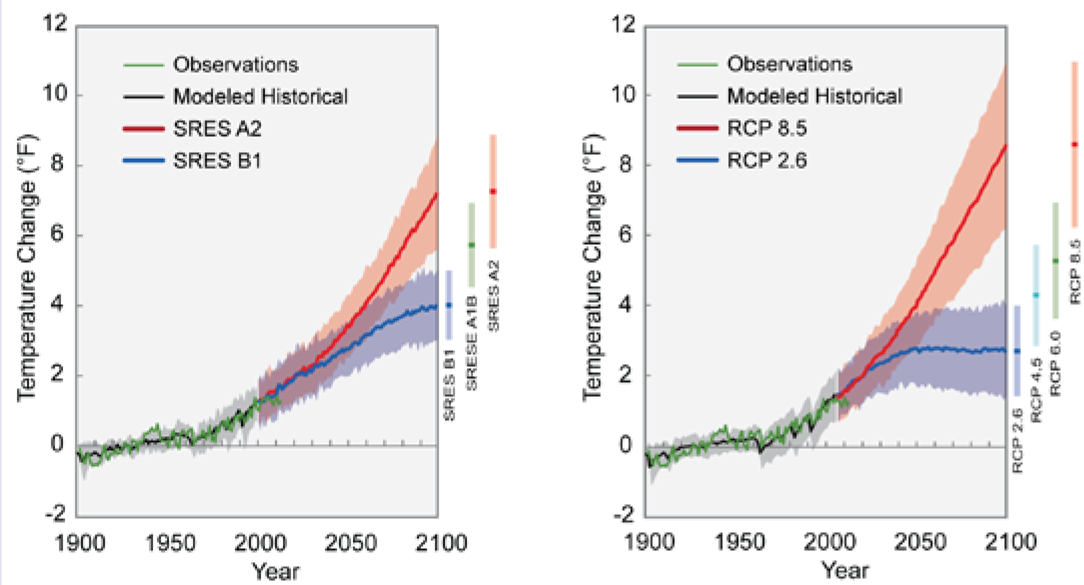

Figure 23. Projected global average annual temperature changes for multiple future scenarios relative to the 1901-1960 average temperature. Each line represents a central estimate of global average temperature rise for a specific emissions pathway. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. The left panel shows results from the previous generation of climate models (CMIP3), and the right panel shows results from the most recent generation of climate models (CMIP5). Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. (Data from CMIP3, CMIP5, and NOAA NCDC).

tions of the climate system have expanded substantially since the beginning of the satellite era, but are still limited. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and turbulent mixing of air). As a result, different models produce slightly different projections of change, even when the models use the same scenarios. Scientists often use multiple models in order to represent this range of projected outcomes.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in future projections. For example, as the Arctic warms, carbon trapped in permafrost may be released into the atmosphere, increasing the initial warming due to human emissions of heat-trapping gases (see FAQ T).

However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, determined not only from the differences in the "climate sensitivity" among models but also from information about climate changes in the past.

T. Are there tipping points in the climate system?

Most climate studies have considered only relatively gradual, continuous changes in the Earth's climate system. However, there are a number of potential "tipping points" in the climate system – points where a threshold is crossed, resulting in a substantial change in the future state of the climate system, regionally and/or globally.

Scientists have identified several aspects of the climate system that could pass a tipping point and/or change substantially under projected climate change (see Figure 24 for key examples). These tipping points have been identified based on observations of past abrupt climate changes, recent observations showing abrupt changes underway (for example, in the Arctic), process-based understanding of the dynamics of the climate system, and climate simulations showing tipping points in future projections. There is no clear scientific consensus at this time as to whether major tipping points, other than loss of the Arctic sea ice in summer, will be reached during this century.

Some tipping points are more imminent, and some would have larger impacts than others. For example, the rapid decline of Arctic sea ice exposes the darker ocean surface which absorbs increasing amounts of heats and reduces the amount of new seasonal ice formed. This drastic reduction in sea ice can tip the Arctic Ocean into a permanent, nearly ice-free state in summer (Ch.2: Our Changing Climate, Key Message 11). There is some

Potential Tipping Points

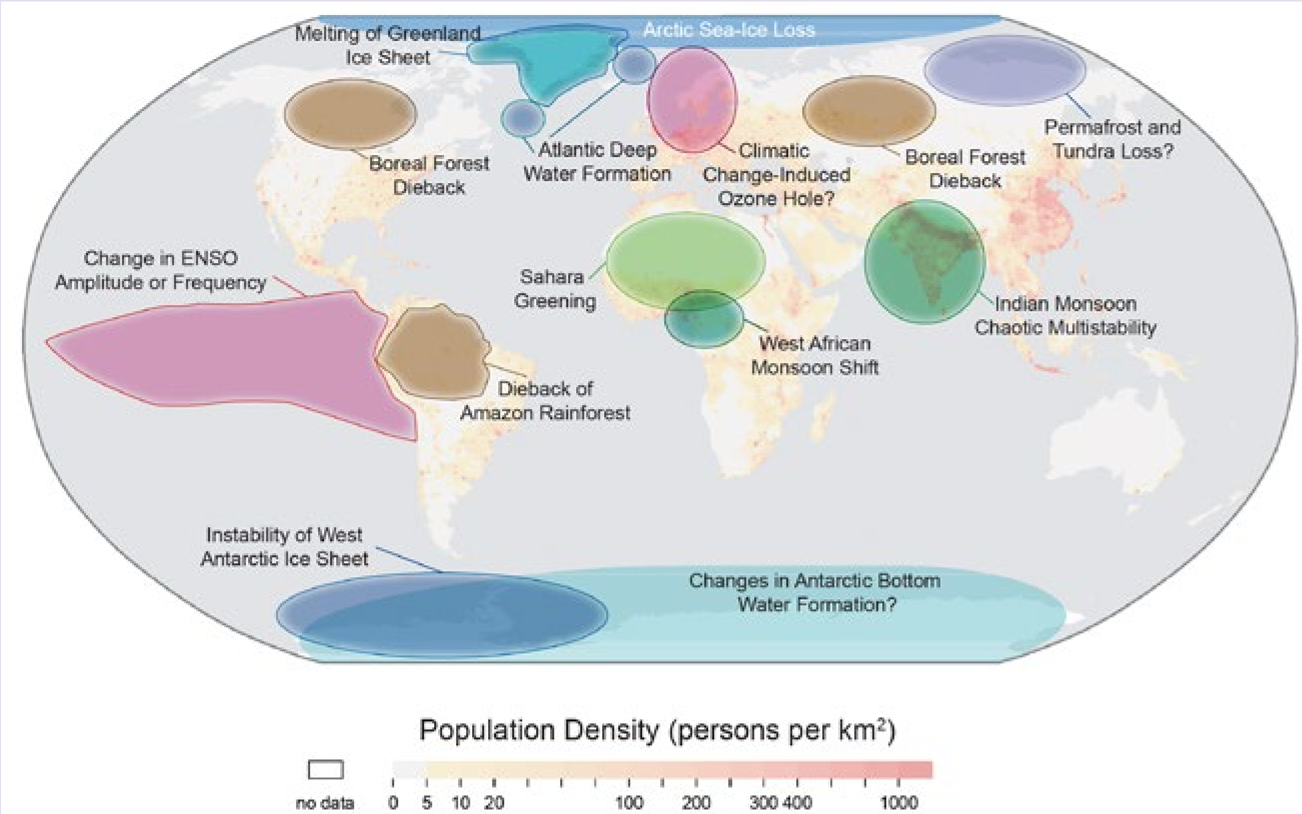

Figure 24. Stylized map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain. (Figure source: adapted from Lenton et al. 2008[17])

evidence that reductions in ice cover are already leading to changes in weather patterns affecting the U.S. and Europe.

Currently, the proximity, rate, and reversibility of tipping points are usually assessed through a mixture of climate modeling, literature review, and expert elicitation. However, there is a need for more research in this area. Climate scientists cannot predict when tipping points will be crossed because of uncertainties in the climate system and because we do not know what pathway future emissions will take. But an absence of certainty does not indicate an absence of risk. To use a medical analogy, just because your doctor cannot tell you the precise date and time that you will have a heart attack does not mean you should ignore medical advice to reduce your risk by taking preventative measures like exercising more, losing weight, and changing your diet. Medical science is imperfect, just like climate science, but it can provide very useful advice regarding the risks of our actions and choices – and the benefits of preventative measures.

U. How is climate change affecting society?

Multiple lines of evidence show that climate change is happening as a result of human activities. Climate change is altering the world around us, and these changes will become increasingly evident with each passing decade. Climate change is already leading to more intense rainfall events and other extreme weather patterns. It will lead to more droughts in some areas, more floods in others, and more frequent heat waves in many areas. Changing temperature and precipitation patterns, as well as increasing sea level, are important factors affecting various parts of the United States. For example, the risks associated with wildfires in the western U.S. are increasing, and coastal inundation is becoming a common occurrence in low-lying areas. Water supply availability is changing in many parts of the United States.

Many people are already being affected by the changes that are occurring, and more will be affected as these changes continue to unfold. To limit risks and maximize opportunities associated with the changes, it would be helpful for people to understand how climate change could affect them and what they can do to adapt, as well as what can be done to reduce future climate change by reducing global emissions.

Taking actions to reduce the emissions that cause climate change has costs. Not taking those actions has much greater costs.[18]

Climate change will affect ecosystems and human systems – such as agricultural, transportation, water resources, and health-related infrastructure – in ways we are only beginning to understand. Moreover, climate change interacts with other stressors, such as population increase, land-use change, and economic and political changes, in ways that we may not be able to anticipate, compounding the risks.

In general, the larger and faster the changes in climate, the more difficult it is for human and natural systems to adapt. The climate system has been relatively stable during the time that human civilizations have existed. Essentially, today's built infrastructure has been developed based on the assumption that future climate will be like that of the past. This assumption is no longer valid.

Since climate change is already occurring, adaptation in some form is inevitable. The choice is between proactive adaptation (planning ahead to limit impacts) or reactive adaptation (where responses occur only after damages are already incurred). The *America's Climate Choices* reports from the U.S. National Academy of Sciences discuss these issues in details.

Potential Effects of Climate Change

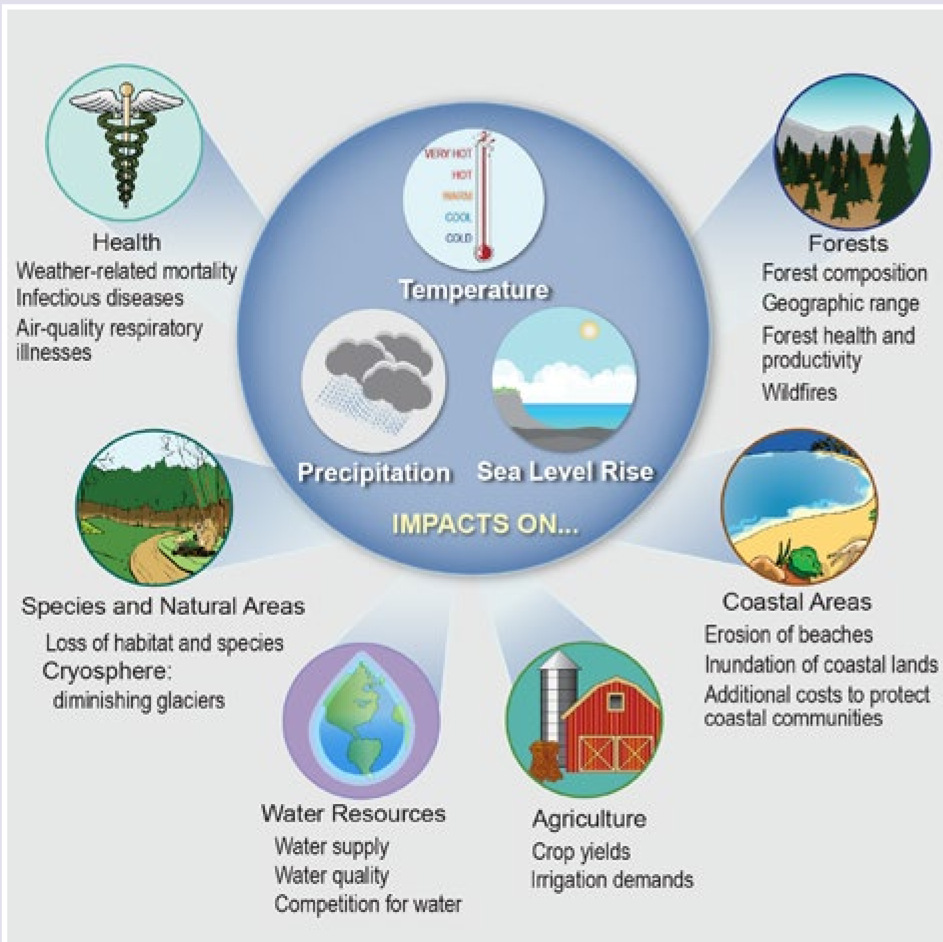

Figure 25. Climate change is likely to affect human society and the natural environment in many ways. The National Climate Assessment's sectoral impacts chapters examine these impacts by category in detail. (Figure source: adapted from Phillipe Rekacewicz UNEP/GRID-Arendal 2012, "Vital Climate Graphics" collection[19]).

V. Are there benefits to warming?

Some climate changes currently have beneficial effects for specific sectors or regions. For example, current benefits of warming include longer growing seasons for agriculture and longer ice-free periods for shipping on the Great Lakes. At the same time, however, longer growing seasons, along with higher temperatures and carbon dioxide, 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 there will be more negative effects than positive ones. This is largely because our society and infrastructure have been built for the climate of the past, and any rapid change from that climate imposes difficulties and costs. For example, many major cities are located on the coasts where they are now vulnerable to sea level rise. And there has been rapid population growth in the U.S. Southwest, where increasing heat and drought threaten water supplies and cause increased wildfires. In addition, ecosystems that we rely on for our food and water are adapted to the cooler climate that our planet has experienced over recent centuries.

W. Are some people more vulnerable than others?

People will be affected by climate change in various ways, but some groups are more vulnerable than others. For example, the poor, the very young, and some older people have less mobility and fewer resources to cope with extremely high temperatures, increased water scarcity, environmental degradation, and other impacts. People living in flood plains, coastal zones, and some urban areas are generally more vulnerable as well.

Children, primarily because of physiological and developmental factors, will disproportionately suffer from the effects of heat waves, air pollution, infectious illness, and trauma resulting from extreme weather events. The country's older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events. Pre-existing health conditions also make older adults susceptible to cardiac and respiratory impacts of air pollution and to more severe consequences from infectious diseases. Limited mobility among older adults can also increase flood-related health risks. Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups. Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population.

X. Are there ways to reduce climate change?

The most direct way to significantly reduce the magnitude of future climate change is to reduce the emissions of heat-trapping gases. Emissions can be reduced in many ways, and increasing the efficiency of energy use is an important component of many potential strategies. For example, because about 28% of the energy used in the U.S. is used for transportation, developing and driving more efficient vehicles and changing to fuels that do not contribute significantly to heat-trapping gas emissions over their lifetimes would result in fewer emissions per mile driven. A large amount of energy in the U.S. is also used to heat and cool buildings, so changes in building design could dramatically reduce energy use. While there is no single silver bullet that will solve all the challenges posed by climate change, there are many options that can reduce our emissions and help prevent some of the potentially serious impacts of climate change. There will be some costs to these changes, but even very ambitious emissions reductions targets have relatively small costs over the decades it will take to implement them.

Because impacts are already occurring and anticipated to increase, adaptation to the impacts of climate change will be required. Adaptation decisions range from being better prepared for extreme events such as floods and droughts, to identifying economic opportunities that come from investments in adaptation and mitigation strategies and technologies, to integrating considerations of new climate-related risks into city planning, public health and emergency preparedness, and ecosystem management.

Technological fixes such as "geoengineering" may be possible, but at least some such proposals would do nothing to slow ocean acidification, and would need to be done indefinitely. There are a wide variety of potential risks of geoengineering schemes, which are very poorly understood (see FAQ Z).

Multiple Pathways for Reducing U.S. Emissions

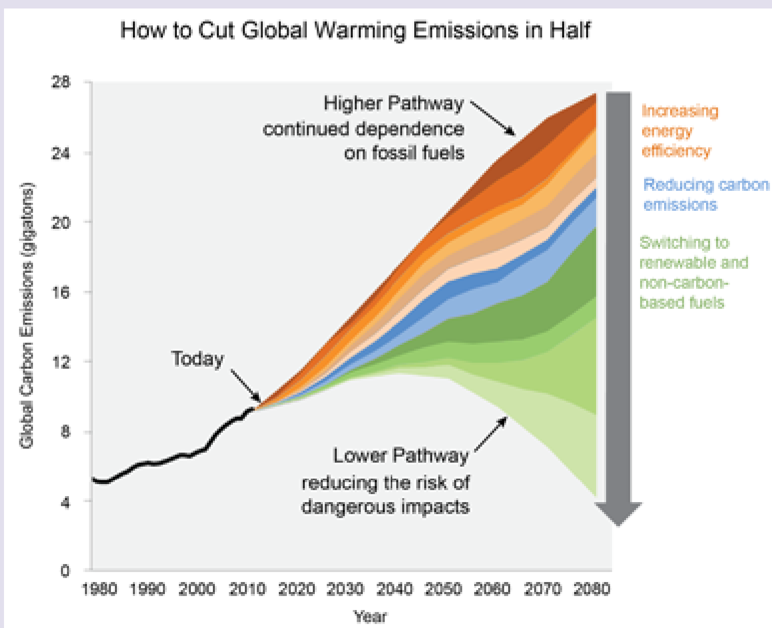

Figure 26. Reducing carbon emissions from a higher pathway (here, RCP 8.5) to a lower pathway (here, RCP 4.5) can be accomplished with a combination of many technologies and policies, illustrated here based on the "wedges" concept pioneered by Pacala and Socolow in 2004.[20] These wedges could include 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. (Data from Boden et al. 2012[21]).

Y. Are there advantages to acting sooner rather than later?

The effects of current emissions of carbon dioxide and other heat-trapping gases on climate can take decades to fully manifest themselves. The resulting change in climate and the impacts of those changes can then persist for a long time. The longer these changes in climate continue, the greater the resulting impacts. It will become increasingly costly to adapt, and some systems will not be able to adapt if the change is too much or too fast. Thus it is not surprising that recent reports from the U.S. National Academy of Sciences, including America's Climate Choices[22] and America's Energy Future,[23] have concluded that the environmental, economic, and humanitarian risks posed by climate change indicate a pressing need for substantial action to limit the magnitude of climate change and to prepare to adapt to its impacts. They also concluded that substantial reductions of heat-trapping gas emissions should be among the nation's highest priorities.

The National Academy of Sciences and others have concluded that acting now will reduce the risks posed by climate change and the pressure to make larger, more rapid, and potentially more expensive reductions later. Actions taken to reduce vulnerability to climate change impacts can be considered as investments that can make sense economically, especially if they also offer protection against natural climate variations and extreme events. In addition, investment decisions made now about equipment and infrastructure can "lock in" emissions of heat-trapping gases for decades to come. Finally, while it may be possible to alter our responses to climate change, it is difficult or impossible to "undo" climate change once it has occurred.

Current efforts at local and state levels, and by the private sector, are important, but are insufficient to limit warming to the lower scenarios described throughout this report. Thus, numerous analyses have called for policies that establish coherent national and international goals and incentives, and that promote strong U.S. engagement in international-level response efforts. The National Academy of Sciences found that the inherent complexities and uncertainties of climate change will be best met by applying a risk management approach and by making efforts to significantly reduce heat-trapping gas emissions; prepare for adapting to impacts; invest in scientific research, technology development, and information systems; and facilitate engagement between scientific and technical experts and the many types of people making America's climate choices.

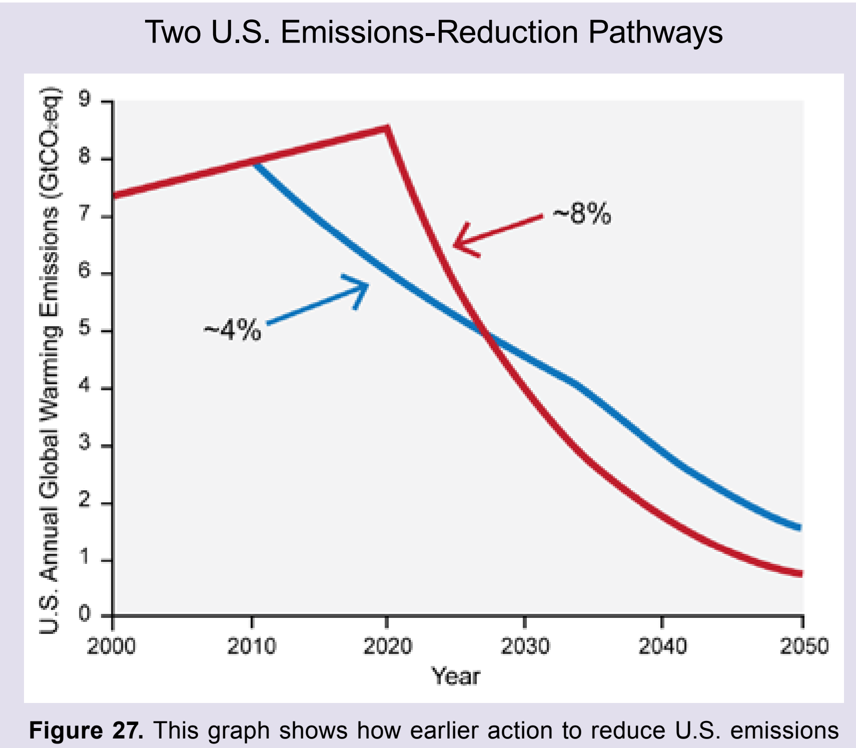

Figure 27. This graph shows how earlier action to reduce U.S. emissions would be less difficult than delayed action. Two pathways show how a cumulative carbon emissions budget of 265 gigatons of CO_2 could be maintained by 2050. By initiating reduced emissions efforts in 2010 (blue line), a 4% per year reduction would have been required; waiting until 2020 to reduce emissions (red line) doubles the rate at which emissions must be reduced. (Figure source: Luers et al. 2007[24])

Z. Can we reverse global warming?

While we can't stop climate change in its tracks, we can limit it to less dangerous levels by reducing our emissions. Even if all human-related emissions of carbon dioxide and the other heat-trapping gases were to stop today, Earth's temperature would continue to rise for a number of decades and then slowly begin to decline. However, focusing on short-lived types of emissions, such as methane and black carbon (soot), can reduce the rate of change in the near term. Because of the complex processes controlling carbon dioxide concentrations in the atmosphere, even after more than a thousand years, the global temperature would still be higher than it was in the pre-industrial period. As a result, without technological intervention, it will not be possible to totally reverse climate change. We do face a choice between a little more warming and lot more warming, however. The amount of future warming will depend on our future emissions.

In theory, it may be possible to reverse global warming through technological interventions called geoengineering. Three types of geoengineering approaches have been proposed to alter the climate system: 1) enhancing the natural processes that remove carbon dioxide from the atmosphere; 2) altering the amount of the sun's energy that reaches the Earth (referred to

Emissions Reductions and Carbon Dioxide Concentrations

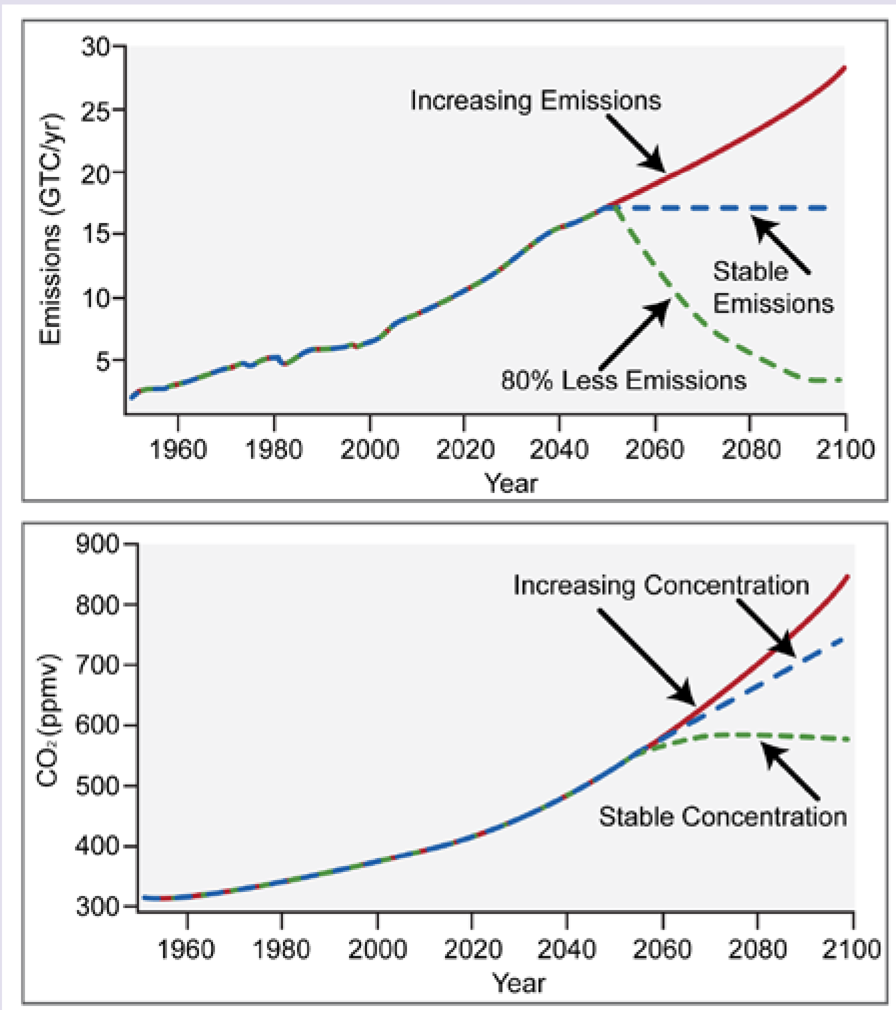

Figure 28. To reduce the changes occurring in climate, we would need to stabilize atmospheric levels of carbon dioxide, not simply stabilize current emission levels of carbon dioxide. Just stabilizing emissions still leads to increasing amounts of carbon dioxide in the atmosphere, because emissions are greater than the sinks that remove it (blue lines). To stabilize levels of atmospheric carbon dioxide, emissions would need to be reduced significantly, on the order of 80% or more compared to the present day (green lines). The lower graph shows how carbon dioxide concentrations would be expected to evolve depending upon emissions for one illustrative case, but this applies for any chosen target. (Figure source: NRC 2011[25]).

as “solar radiation management”); and 3) direct capture and storage of CO_2 from the atmosphere.

Various techniques for removal of carbon dioxide from the atmosphere have been proposed. At this time, however, there is no indication that any of them could be implemented on a large enough scale to have a significant effect. Investments in limiting emissions, combined with capturing and storing carbon, could possibly reverse the warming trend, but it remains to be seen if this is feasible.

Artificial injection of stratospheric particles and cloud brightening are two examples of “solar radiation management” techniques. The cooling effect that some types of particles have on the atmosphere has led to the proposal of an array of possible geoengineering projects, especially with the goal of offsetting the warming until more non-fossil fuel energy is put into place. However, the climate system is complex and experimenting without complete understanding could result in unintended and potentially dangerous side effects on our health, ecosystems, agricultural yields, and even the climate itself. Even if such engineering approaches were economically feasible, the potential impacts on the environment need to be better understood. One important consideration regarding solar radiation management is that ocean acidification would still continue even if warming could otherwise be reduced by reflecting light away from our atmosphere. Much more research is needed to see if such approaches could be environmentally feasible. In the meantime, there are significant concerns about ecological and other side effects of some of these technologies.

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APPENDIX 5 SCENARIOS AND MODELS

Scenarios

Scenarios provide ways to help understand what future conditions might be. Each scenario provides an example of what might happen under particular assumptions, and is neither a prediction nor a forecast. Instead, scenarios provide scientifically rigorous and consistent starting points for examining questions about an uncertain future and help us to visualize alternative futures in human terms. The military and businesses frequently use these powerful tools for future planning in high-stakes situations. Scenarios are used to help identify future vulnerabilities as well as to support decision-makers who are focused on limiting risk and maximizing opportunities. Three types of scenarios are used within this assessment to help frame the impact analyses in a consistent way: emissions scenarios (including population and land-use components); climate scenarios; and sea level rise scenarios. Each is briefly described below.

Emissions Scenarios

Emissions scenarios quantitatively illustrate how the release of different amounts of climate-altering gases and particles into the atmosphere will produce different future climate conditions. Such emissions result from human activities including fossil fuel energy production and use, agriculture, and other activities that change land use. These scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors. A wide range of assumptions is used because future trends depend on unpredictable human choices.

Perspectives on "plausible" emissions scenarios evolve over time. The Intergovernmental Panel on Climate Change (IPCC) has released three different sets of scenarios since 1990. In 2000, the IPCC released a Special Report on Emission Scenarios[1] that provided a set of scenarios, known as the SRES, which described a wide range of socioeconomic futures and resulting emissions. Near the higher end of the range, the SRES A2 scenario represents a world with high population growth, low economic growth, relatively slow technology improvements and diffusion, and other factors that contribute to high emissions and lower adaptive capacity (for example, low per capita wealth). At the lower end of the range, the SRES B1 scenario represents a world with lower population growth, higher economic development, a shift to low-emitting efficient energy technologies that are diffused rapidly around the world through free trade, and other conditions that reduce the rate and magnitude of climate change as well as increase capacity for adaptation. The SRES A2 and B1 scenarios are the foundation scenarios used in this assessment to evaluate future impacts.

Recently, a new set of scenarios (Representative Concentration Pathways – RCPs) has been prepared and released by scientists who study emissions, climate, and potential impacts.[2] This new set incorporates recent observations and research and includes a wider range of future conditions and emissions. Because climate model results are just now being released using the new scenarios, and there are few impact studies that employ them, the RCP climate scenarios are used sparingly in this assessment.

Scientists cannot predict which, if any, of the scenarios in either the SRES set or the RCP set is most likely because the future emissions pathway is a function of human choices. A wide range of societal decisions and policy choices will ultimately influence how the world's emissions evolve, and ultimately, the composition of the atmosphere and the state of the climate system.

Climate Scenarios and Climate Models

Global models that simulate the Earth's climate system are used, among other things, to evaluate the effects of human activities on climate. This assessment incorporates a new set of model simulations that have higher resolution and enhanced representation of Earth system physics, chemistry, and biology. These models use the new set of RCP emissions scenarios described above to project expected climate change given various assumptions about how human activities and associated emissions levels might change.

The range of potential increases in global average temperature in the newest climate model simulations is wider than earlier simulations because a broader range of options for human behavior is considered. For example, the lowest of the new RCP scenarios assumes rapid emissions reductions that would limit the global temperature increase to about 3.7°F, a much lower level than in previous scenarios. The emissions trajectory in RCP 8.5 is similar to SRES A2 and RCP 4.5 is roughly comparable to SRES B1 (see Figure 1). These similarities between specific RCP and SRES scenarios make it possible to compare the results from different modeling efforts over time.

Emissions Levels Determine Temperature Rises

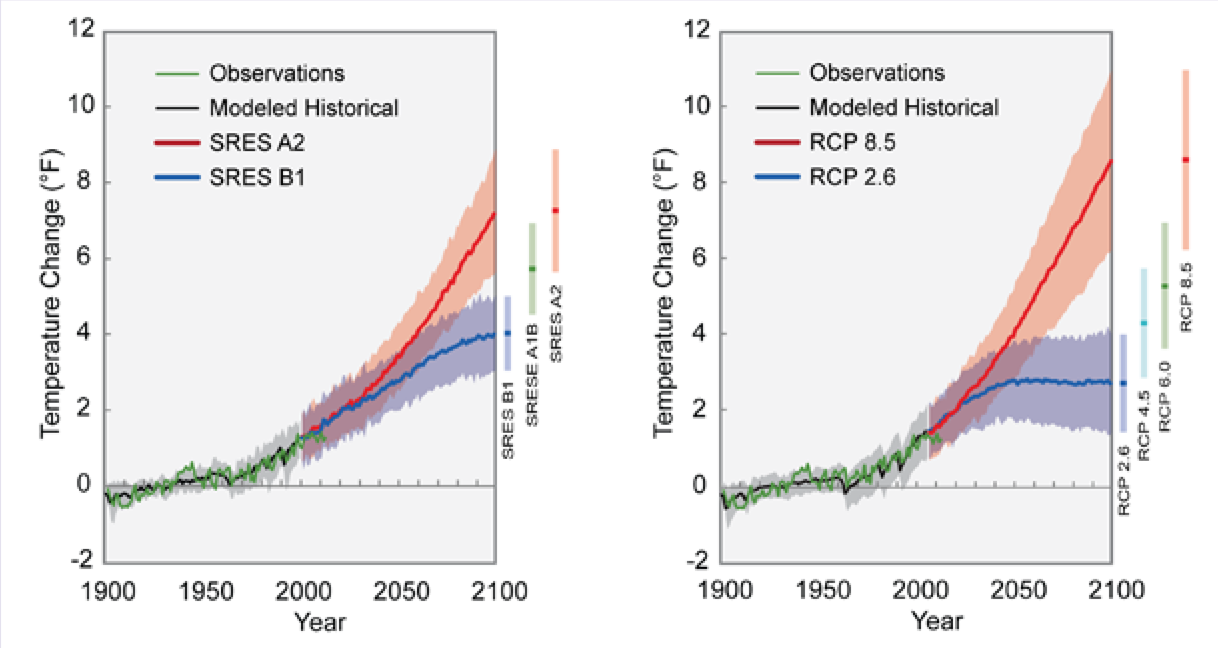

Figure 1. Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth's temperature. In the figure, each line represents a central estimate of global average temperature rise for a specific emissions pathway (relative to the 1901-1960 average). Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. **(Left)** The panel shows the two main scenarios (SRES – Special Report on Emissions Scenarios) used in this report: A2 assumes continued increases in emissions throughout this century, and B1 assumes much slower increases in emissions beginning now and significant emissions reductions beginning around 2050, though not due explicitly to climate change policies. **(Right)** The panel shows newer analyses, which are results from the most recent generation of climate models (CMIP5) using the most recent emissions pathways (RCPs – Representative Concentration Pathways). Some of these new projections explicitly consider climate policies that would result in emissions reductions, which the SRES set did not.[35] The newest set includes both lower and higher pathways than did the previous set. The lowest emissions pathway shown here, RCP 2.6, assumes immediate and rapid reductions in emissions and would result in about 2.5°F of warming in this century. The highest pathway, RCP 8.5, roughly similar to a continuation of the current path of global emissions increases, is projected to lead to more than 8°F warming by 2100, with a high-end possibility of more than 11°F. (Data from CMIP3, CMIP5, and NOAA NCDC).

Emissions Scenarios

Two SRES global emissions scenarios were recommended for use by the authors of this report for impact studies. One is a higher emissions scenario (the A2 scenario from SRES) and the other is a lower emissions scenario (the B1 scenario from SRES). These two scenarios do not encompass the full range of possible futures: emissions could change less than those scenarios imply, or they could change even more. Recent carbon dioxide emissions have, in fact, been higher than in the A2 scenario. Whether this trend will continue is not possible to predict because it depends on societal choices.

Sea Level Rise Scenarios

After at least two thousand years of little change, global sea level rose by roughly 8 inches over the last century, and satellite data provide evidence that the rate of rise over the past 20 years has roughly doubled. In the United States, millions of people and many of the nation's assets related to military readiness, energy, transportation, commerce, and ecosystems are located in areas at risk of increased coastal flooding because of sea level rise and associated storm surge.

Global sea level is rising and will continue to do so beyond the year 2100 as a result of increasing global temperatures. This occurs for two main reasons. First, when temperatures rise, ocean water heats up, causing it to expand. Second, when glaciers and ice sheets melt in response to hotter conditions, additional water flows into the oceans. Sea level is projected to rise an additional 1 to 4 feet in this century. Scientists are unable to narrow this range at present because the processes affecting the loss of ice mass from the large ice sheets are dynamic and still the subject of intense study.

Some impact assessments in this report use a set of sea level rise scenarios within this range, while others consider a wider range. Four scenarios (8 inches, 1 foot, 4 feet, and 6.6 feet of rise by 2100), along with explanations regarding how to use this information, are included in a guidance document on sea level rise that was provided to the National Climate Assessment (NCA) authors to use as the basis of impact assessments in coastal areas.[3]

Past and Projected Changes in Global Sea Level

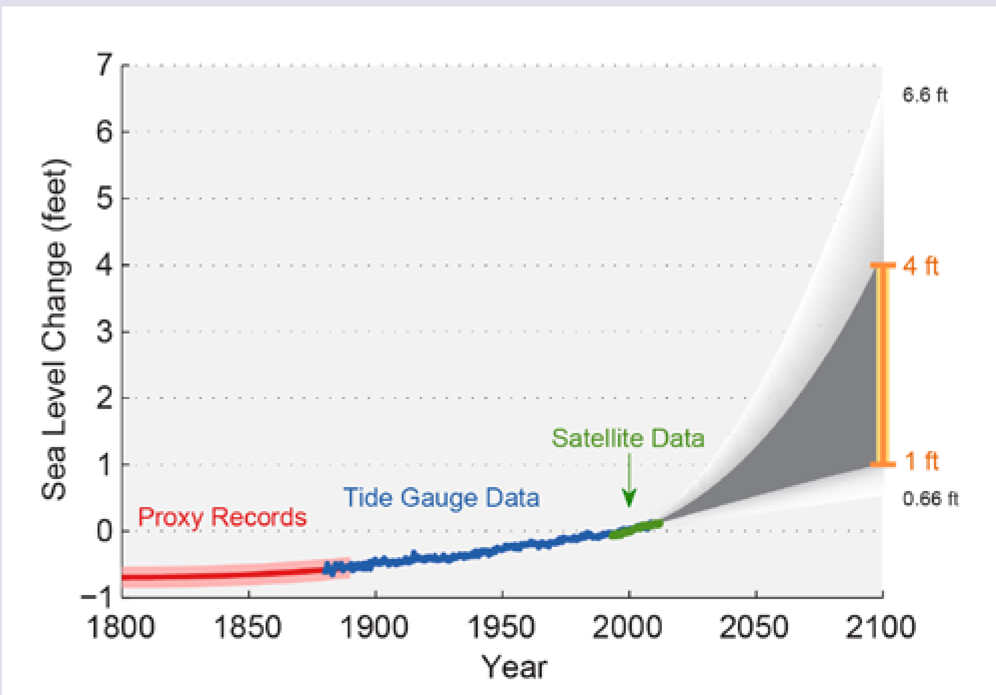

Figure 2. Historical, observed, and possible future amounts of global sea level rise from 1800 to 2100. Historical estimates[4] (based on sediment records and other proxies) are shown in red (pink band shows uncertainty range), tide gauge measurements in blue,[5] and satellite observations in green.[6] The future scenarios displayed here range from 8 inches to 6.6 feet in 2100.3 Sea level rise lower than 8 inches or higher than 6.6 feet is considered implausible by 2100. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100. The large range primarily reflects uncertainty about how ice sheets will respond to the warming ocean and atmosphere, and to changing winds and currents. (Figure source: NASA Jet Propulsion Laboratory).

Models and Sources of Uncertainty

There are multiple well-documented sources of uncertainty in climate model simulations. Some of these uncertainties can be reduced with improved models. Some may never be completely eliminated. The climate system is complex, including natural variability on a range of time scales, and this is one source of uncertainty in projecting future conditions. In addition, there are challenges with building models that accurately represent the physics of multiple interacting processes, with the scale and time frame of the available historical data, and with the ability of computer models to handle very large quantities of data. Thus, climate models are necessarily simplified representations of the real climate system.

One of the largest sources of uncertainty in projecting future conditions involves what decisions society will make about managing the emissions of greenhouse gases. By later this century, very different conditions would result from higher emissions scenarios (such as A2) than from lower ones (like B1).

Over the last decade, concerted efforts in climate modeling have focused on understanding and better quantifying the uncertainties inherent in model simulations of climate change and on improving model resolution and representations of physical and biological processes important to the climate system. It is very clear that progress is being made in the accuracy of models in representing the physics of the climate system at smaller scales. This is demonstrated, for example, by the ability of these models to replicate observed climate.

To understand and better quantify uncertainty, multiple models generated by different modeling groups around the world are being used to identify common features in projections of climate change. The Third Coupled Model Intercomparison Project (CMIP3), and more recently CMIP5, established formalized structures that enable model evaluations against the climate record of the recent past. New elements of the CMIP5 effort include a major focus on near-term, decade-length projections designed for regional climate change and on predictions from the new class of Earth system models that include coupled physical, chemical, and biogeochemical climate processes. CMIP3 findings are the foundation for most of the impact analyses included in this assessment. Newer information from CMIP5 was largely unavailable in time to serve as the foundation for this report and is primarily provided for comparison purposes.

The breadth and depth of these analyses indicate that the modeling results in this report are robust. There is an important distinction to be made, however, between a "prediction" of what "will" happen and a "projection" of what future conditions are likely given a particular set of assumptions. All of the model results presented in this report are the latter: projections based on specified assumptions about emissions. The new regional projections provided in this report represent the state of the science in climate change modeling.[7]

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APPENDIX 6 TOPICS FOR CONSIDERATION IN FUTURE ASSESSMENTS

Although this report covers a broad range of topics related to understanding, assessing, and responding to global change as required by the Global Change Research Act,1 it is not possible to provide a comprehensive analysis of every topic in a single report. The following are important topics that could not be adequately covered in this report. In preparation for future synthesis reports, these are some topics that could be considered.

Economic Analyses

Documenting the costs of climate change impacts is extremely challenging because these impacts occur across multiple regions and sectors and over multiple time frames. The impacts include physical, ecological, and social components, and many are difficult to extract from underlying sources of vulnerability not caused by climate change. Also, while some types of extreme weather events are made more frequent and/or intense by climate change, it is rare that any event has a single cause. Since such events generally result from a combination of natural variability and climate change, it is difficult to assign a precise proportion of the costs associated with a particular event to climate change. Further, many impacts occur in ways that are difficult to translate into precise economic costs; for example, impacts to biodiversity, changes in quality of life, or social stresses are likely to be valued differently by different individuals and communities. Finally, it is challenging to assess the economic implications of rare events, which have low probability but high consequence – especially in cases where there is limited or non-existent data about the costs of such events in the past.

A number of studies have produced estimates of the economic damages expected from future climate change. However, there are currently no total economic damage estimates that are based on valuing and aggregating the various regional and sectoral impacts that are the focus of this assessment. Understanding these impacts in more detail could provide important input for adaptation and mitigation decisions.

National Security

The implications of climate change for U.S. national security are significant, but they have not been analyzed in detail in this report because there are a number of recent unclassified U.S. Department of Defense (DoD) reports and reports of other groups that have rigorously addressed this topic. In 2010, the DoD released the Quadrennial Defense Review (QDR), for the first time acknowledging that climate change will play a "significant role in shaping the future security environment."2 Based on the QDR, the DoD is now incorporating and considering the consequences of climate change in its long-range strategic plans, including potential impacts to its facilities and missions. Other recent reports by the National Intelligence Council and the National Research Council (NRC) analyze the security implications of climate change.3 The NRC found that "It is prudent to expect that over the course of a decade some climate events…will produce consequences that exceed the capacity of the affected societies or global systems to manage and that have global security implications serious enough to compel international response." National security concerns are highly integrated with a variety of other economic, health, policy and resource management issues. The findings of the National Climate Assessment reports, as well as other environmental assessments, are influential in determining threats to national security. It will be useful in future reports to advance the state of knowledge of climate impacts in a manner that would improve the ability of the appropriate government institutions to determine how such impacts are integrated in complex ways with national security concerns and emergency preparedness.

Interactions between Adaptation and Mitigation Activities

An additional topic that requires further investigation is the state of knowledge of the intersections of adaptation and mitigation activities. Although adaptation, preparedness, and resilience are all related concepts, the emissions implications across the life of an adaptation project, including full assessment of the emissions associated with "supply chains" for manufactured goods and services, are difficult to assess for any project, and even more challenging on larger scales. In addition, there are options where mitigation and adaptation strategies have co-benefits and other combinations of strategies that can cause unintended negative consequences. For example, the water resource implications of increased production of biofuels are substantial in some regions of the United States, and may result in negative impacts on ecosystems, power production, or residential water supply (see Ch. 6: Agriculture; Ch. 10: Energy, Water, and Land; Ch. 27: Mitigation; and Ch. 28: Adaptation). It would be useful to explore these and related topics in more detail in future assessments.

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