U.S. Global Change Research Program

Fourth National Climate Assessment

Volume II

Impacts, Risks, and Adaptation in the United States

Report-in-Brief

Full report available online at: nca2018.globalchange.gov

Image credit

Front cover: *National Park Service*; **back cover:** *NASA Earth Observatory image by Joshua Stevens, using Landsat data from the U.S. Geological Survey.*

In August 2018, temperatures soared across the northwestern United States. The heat, combined with dry conditions, contributed to wildfire activity in several states and Canada. The cover shows the Howe Ridge Fire from across Lake McDonald in Montana's Glacier National Park on the night of August 12, roughly 24 hours after it was ignited by lightning. The fire spread rapidly, fueled by record-high temperatures and high winds, leading to evacuations and closures of parts of the park. The satellite image on the back cover, acquired on August 15, shows plumes of smoke from wildfires on the northwestern edge of Lake McDonald.

Wildfires impact communities throughout the United States each year. In addition to threatening individual safety and property, wildfire can worsen air quality locally and, in many cases, throughout the surrounding region, with substantial public health impacts including increased incidence of respiratory illness (Ch. 13: Air Quality, KM 2; Ch. 14: Health, KM 1; Ch. 26: Alaska, KM 3). As the climate warms, projected increases in wildfire frequency and area burned are expected to drive up costs associated with health effects, loss of homes and infrastructure, and fire suppression (Ch. 6: Forests, KM 1; Ch. 17: Complex Systems, Box 17.4). Increased wildfire activity is also expected to reduce the opportunity for and enjoyment of outdoor recreation activities, affecting quality of life as well as tourist economies (Ch. 7: Ecosystems, KM 3; Ch. 13: Air Quality, KM 2; Ch. 14: Tribal, KM 1; Ch. 19: Southeast, KM 3; Ch. 24: Northwest, KM 4).

Human-caused climate change, land use, and forest management influence wildfires in complex ways (Ch. 17: Complex Systems, KM 2). Over the last century, fire exclusion policies have resulted in higher fuel availability in most U.S. forests (CSSR, Ch. 8.3, KF 6). Warmer and drier conditions have contributed to an increase in the incidence of large forest fires in the western United States and Interior Alaska since the early 1980s, a trend that is expected to continue as the climate warms and the fire season lengthens (Ch. 1: Overview, Figure 1.2k; CSSR, Ch. 8.3, KF 6). The expansion of human activity into forests and other wildland areas has also increased over the past few decades. As the footprint of human settlement expands, fire risk exposure to people and property is expected to increase further (Ch. 5: Land Changes, KM 2).

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NCA4

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About This Report

The National Climate Assessment

The Global Change Research Act of 1990 mandates that the U.S. Global Change Research Program (USGCRP) deliver a report to Congress and the President no less than every four years that "1) integrates, evaluates, and interprets the findings of the Program . . .; 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."[1]

The Fourth National Climate Assessment (NCA4) fulfills that mandate in two volumes. This report, Volume II, draws on the foundational science described in Volume I, the *Climate Science Special Report* (CSSR).[2] Volume II focuses on the human welfare, societal, and environmental elements of climate change and variability for 10 regions and 18 national topics, with particular attention paid to observed and projected risks, impacts, consideration of risk reduction, and implications under different mitigation pathways. Where possible, NCA4 Volume II provides examples of actions underway in communities across the United States to reduce the risks associated with climate change, increase resilience, and improve livelihoods.

This assessment was written to help inform decision-makers, utility and natural resource managers, public health officials, emergency planners, and other stakeholders by providing a thorough examination of the effects of climate change on the United States.

Climate Science Special Report: NCA4 Volume I

The *Climate Science Special Report* (CSSR), published in 2017, serves as the first volume of NCA4. It provides a detailed analysis of how climate change is affecting the physical earth system across the United States and provides the foundational physical science upon which much of the assessment of impacts in this report is based. The CSSR integrates and evaluates current findings on climate science and discusses the uncertainties associated with these findings. It analyzes trends in climate change, both human-induced and natural, and projects major trends to the end of this century. Projected changes in temperature, precipitation patterns, sea level rise, and other climate outcomes are based on a range of scenarios widely used in the climate research community, referred to as Representative Concentration Pathways (RCPs). As an assessment and analysis of the physical science, the CSSR provides important input to the development of other parts of NCA4 and their primary focus on the human welfare, societal, economic, and environmental elements of climate change. A summary of the CSSR is provided in Chapter 2 (Our Changing Climate) of this report; the full report can be accessed at science2017.globalchange.gov.

About the Report-in-Brief

The NCA4 Volume II Report-in-Brief presents overall Summary Findings, an Overview that synthesizes material from the underlying chapters, and Executive Summaries for each chapter of this volume.

The 186-page Report-in-Brief is available as a downloadable PDF at https://nca2018.globalchange.gov/downloads.

Report Development, Review, and Approval Process

The National Oceanic and Atmospheric Administration (NOAA) served as the administrative lead agency for the preparation of this report. A Federal Steering Committee, composed of representatives from USGCRP agencies, oversaw the report's development.

A team of more than 300 federal and non-federal experts—including individuals from federal, state, and local governments, tribes and Indigenous communities, national laboratories, universities, and the private sector—volunteered their time to produce the assessment, with input from external stakeholders at each stage of the process. A series of regional engagement workshops reached more than 1,000 individuals in over 40 cities, while listening sessions, webinars, and public comment periods provided valuable input to the authors. Participants included decision-makers from the public and private sectors, resource and environmental managers, scientists, educators, representatives from businesses and nongovernmental organizations, and the interested public.

NCA4 Volume II was thoroughly reviewed by external experts and the general public, as well as the Federal Government (that is, the NCA4 Federal Steering Committee and several rounds of technical and policy review by the 13 federal agencies of the USGCRP). An expert external peer review of the whole report was performed by an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine (NASEM).[3] Additional information on the development of this assessment can be found in Appendix 1: Report Development Process.

Sources Used in This Report

The findings in this report are based on an assessment of the peer-reviewed scientific literature, complemented by other sources (such as gray literature) where appropriate. In addition, authors used well-established and carefully evaluated observational and modeling datasets, technical input reports, USGCRP's sustained assessment products, and a suite of scenario products. Each source was determined to meet the standards of the Information Quality Act (see Appendix 2: Information in the Fourth National Climate Assessment).

Sustained Assessment Products

The USGCRP's sustained assessment process facilitates and draws upon the ongoing participation of scientists and stakeholders, enabling the assessment of new information and insights as they emerge. The USGCRP led the development of two major sustained assessment products as inputs to NCA4: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*[4] and the *Second State of the Carbon Cycle Report*.[5] In addition, USGCRP agencies contributed products that improve the thoroughness of this assessment, including the U.S. Department of Agriculture's scientific assessment *Climate Change, Global Food Security, and the U.S. Food System*;[6] NOAA's Climate Resilience Tool Kit, Climate Explorer, and State Climate Summaries; the U.S. Environmental Protection Agency's updated economic impacts of climate change report;[7] and a variety of USGCRP indicators and scenario products that support the evaluation of climate-related risks (see Appendix 3: Data Tools and Scenario Products).

USGCRP Scenario Products

As part of the sustained assessment process, federal interagency groups developed a suite of high-resolution scenario products that span a range of plausible future changes (through at least 2100) in key environmental parameters. This new generation of USGCRP scenario products (hosted at https://scenarios.globalchange.gov) includes

- changes in average and extreme statistics of key climate variables (for example, temperature and precipitation),
- changes in local sea level rise along the entire U.S. coastline,
- changes in population as a function of demographic shifts and migration, and
- changes in land use driven by population changes.

USGCRP scenario products help ensure consistency in underlying assumptions across the report and therefore improve the ability to compare and synthesize results across chapters. Where possible, authors have used the range of these scenario products to frame uncertainty in future climate and associated effects as it relates to the risks that are the focus of their chapters. As discussed briefly elsewhere in this Front Matter and in more detail in Appendix 3 (Data Tools and Scenario Products), future scenarios referred to as RCPs provide the global framing for NCA4 Volumes I and II. RCPs focus on outputs (such as emissions and concentrations of greenhouse gases and particulate matter) that are in turn fed into climate models. As such, a wide range of future socioeconomic assumptions, at the global and national scale (such as population growth, technological innovation, and carbon intensity of energy mix), could be consistent with the RCPs used throughout NCA4. For this reason, further guidance on U.S. population and land-use assumptions was provided to authors. See Appendix 3: Data Tools and Scenario Products, including Table A3.1, for additional detail on these scenario products.

Guide to the Report

Summary Findings

The 12 Summary Findings represent a very high-level synthesis of the material in the underlying report. They consolidate Key Messages and supporting evidence from 16 underlying national-level topic chapters, 10 regional chapters, and 2 response chapters.

Overview

The Overview presents the major findings alongside selected highlights from NCA4 Volume II, providing a synthesis of material from the underlying report chapters.

Chapter Text

Key Messages and Traceable Accounts

Chapters are centered around Key Messages, which are based on the authors' expert judgment of the synthesis of the assessed literature. With a view to presenting technical information in a manner more accessible to a broad audience, this report aims to present findings in the context of risks to natural and/or human systems. Assessing the risks to the Nation posed by climate change and the measures that can be taken to minimize those risks helps users weigh the consequences of complex decisions.

Since risk can most meaningfully be defined in relation to objectives or societal values, Key Messages in each chapter of this report aim to provide answers to specific questions about what is at risk in a particular region or sector and in what way. The text supporting each Key Message provides evidence, discusses implications, identifies intersections between systems or cascading hazards, and points out paths to greater resilience. Where a Key Message focuses on managing risk, authors considered the following questions:

- What do we value? What is at risk?
- What outcomes do we wish to avoid with respect to these valued things?
- What do we expect to happen in the absence of adaptive action and/or mitigation?
- How bad could things plausibly get? Are there important thresholds or tipping points in the unique context of a given region, sector, and so on?

These considerations are encapsulated in a single question: What keeps you up at night? Importantly, climate is only one of many drivers of change and risk. Where possible, chapters provide information about the dominant sources of uncertainty (such as scientific uncertainty or socioeconomic factors), as well as information regarding other relevant non-climate stressors.

Each Key Message is accompanied by a Traceable Account that restates the Key Message found in the chapter text with calibrated confidence and likelihood language (see Table 1). These Traceable Accounts also document the supporting evidence and rationale the authors used in reaching their conclusions, while also providing information on sources of uncertainty. More information on Traceable Accounts is provided below.

Our Changing Climate

USGCRP oversaw the production of the *Climate Science Special Report* (CSSR): NCA4 Volume I,[2] which assesses the current state of science relating to climate change and its physical impacts. The CSSR is a detailed analysis of how climate change affects the physical earth system across the United States. It presents foundational information and projections for climate change that improve consistency across

analyses in NCA4 Volume II. The CSSR is the basis for the physical climate science summary presented in Chapter 2 (Our Changing Climate) of this report.

National Topic Chapters

The national topic chapters summarize current and future climate change related risks and what can be done to reduce those risks. These national chapters also synthesize relevant content from the regional chapters. New national topic chapters for NCA4 include Chapter 13: Air Quality; Chapter 16: Climate Effects on U.S. International Interests; and Chapter 17: Sector Interactions, Multiple Stressors, and Complex Systems.

Regional Chapters

Responding to public demand for more localized information—and because impacts and adaptation tend to be realized at a more local level—NCA4 provides greater detail in the regional chapters compared to the national topic chapters. The regional chapters assess current and future risks posed by climate change to each of NCA4's 10 regions (see Figure 1) and what can be done to minimize risk. Challenges, opportunities, and success stories for managing risk are illustrated through case studies.

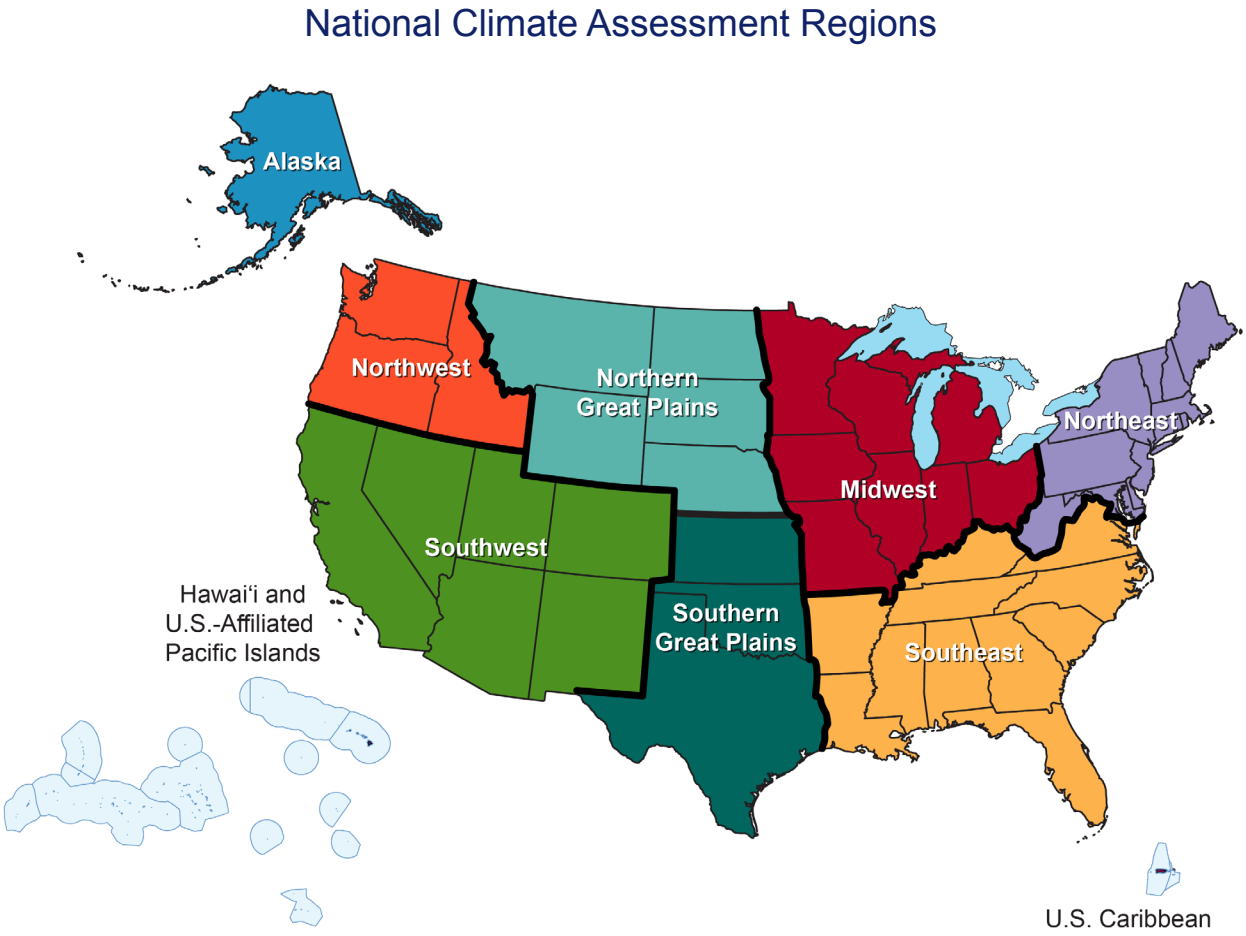

Figure 1: Map of the ten regions used throughout NCA4.

The regions defined in NCA4 are similar to those used in the Third National Climate Assessment (NCA3),[8] with these exceptions: the Great Plains region, formerly stretching from the border of Canada to the border of Mexico, is now divided into the Northern Great Plains and Southern Great Plains along the Nebraska–Kansas border; and content related to the U.S. Caribbean islands is now found in its own chapter, distinct from the Southeast region.

Response Chapters

The response chapters assess the science of adaptation and mitigation, including benefits, tradeoffs, and best practices of ongoing adaptation measures and quantification of economic damages that can be avoided by reducing greenhouse gas emissions. The National Climate Assessment does not evaluate or recommend specific policies.

Economic Estimates

To the extent possible, economic estimates in this report have been converted to 2015 dollars using the U.S. Bureau of Economic Affairs' Implicit Price Deflators for Gross Domestic Product, Table 1.1.9. For more information, please visit: https://bea.gov/national/index.htm. Where documented in the underlying literature, discount rates in specific estimates in this assessment are noted next to those projections.

Use of Scenarios

Climate modeling experts develop climate projections for a range of plausible futures. These projections capture variables such as the relationship between human choices, greenhouse gas (GHG) and particulate matter emissions, GHG concentrations in our atmosphere, and the resulting impacts, including temperature change and sea level rise. Some projections are consistent with continued dependence on fossil fuels, while others are achieved by reducing GHG emissions. The resulting range of projections reflects, in part, the uncertainty that comes with quantifying future human activities and their influence on climate.

The most recent set of climate projections developed by the international scientific community is classified under four Representative Concentration Pathways, or RCPs.[9] A wide range of future socioeconomic assumptions could be consistent with the RCPs used throughout NCA4.

NCA4 focuses on RCP8.5 as a "higher" scenario, associated with more warming, and RCP4.5 as a "lower" scenario with less warming. Other RCP scenarios (e.g., RCP2.6, a "very low" scenario) are used where instructive, such as in analyses of mitigation science issues. To promote understanding while capturing the context of the RCPs, authors use the phrases "a higher scenario (RCP8.5)" and "a lower scenario (RCP4.5)." RCP8.5 is generally associated with higher population growth, less technological innovation, and higher carbon intensity of the global energy mix. RCP4.5 is generally associated with lower population growth, more technological innovation, and lower carbon intensity of the global energy mix. NCA4 does not evaluate the feasibility of the socioeconomic assumptions within the RCPs. Future socioeconomic conditions—and especially the relationship between economic growth, population growth, and innovation—will have a significant impact on which climate change scenario is realized. The use of RCP8.5 and RCP4.5 as core scenarios is broadly consistent with the range used in NCA3.[8] For additional detail on these scenarios and what they represent, please see Appendix 3 (Data Tools and Scenario Products), as well as Chapter 4 of the *Climate Science Special Report*.[10]

Treatment of Uncertainties: Risk Framing, Confidence, and Likelihood

Risk Framing

In March 2016, NASEM convened a workshop, Characterizing Risk in Climate Change Assessments, to assist NCA4 authors in their analyses of climate-related risks across the United States.[11] To help ensure consistency and readability across chapters, USGCRP developed guidance on communicating the risks and opportunities that climate change presents, including the treatment of scientific uncertainties. Where supported by the underlying literature, authors were encouraged to

- describe the full scope of potential climate change impacts, both negative and positive, including more extreme impacts that are less likely but would have severe consequences, and communicate the range of potential impacts and their probabilities of occurrence;
- describe the likelihood of the consequences associated with the range of potential impacts, the character and quality of the consequences, both negative and positive, and the strength of available evidence;
- communicate cascading effects among and within complex systems; and
- quantify risks that could be avoided by taking action.

Additional detail on how risk is defined for this report, as well as how risk-based framing was used, is available in Chapter 1: Overview (see Box 1.2: Evaluating Risks to Inform Decisions).

Traceable Accounts: Confidence and Likelihood

Throughout NCA4's assessment of climate-related risks and impacts, authors evaluated the range of information in the scientific literature to the fullest extent possible, arriving at a series of Key Messages for each chapter. Drawing on guidance developed by the Intergovernmental Panel on Climate Change (IPCC),[12] chapter authors further described the overall reliability in their conclusions using these metrics in their chapter's Traceable Accounts:

- **Confidence** in the validity of a finding based on the type, amount, quality, strength, and consistency of evidence (such as mechanistic understanding, theory, data, models, and expert judgment); the skill, range, and consistency of model projections; and the degree of agreement within the body of literature.
- **Likelihood**, which is based on measures of uncertainty expressed probabilistically (in other words, based on statistical analysis of observations or model results or on the authors' expert judgment).

The author team's expert assessment of confidence for each Key Message is presented in the chapter's Traceable Accounts. Where the authors consider it is scientifically justified to report the likelihood of a particular impact within the range of possible outcomes, Key Messages in the Traceable Accounts also include a likelihood designation. Traceable Accounts describe the process and rationale the authors used in reaching their conclusions, as well as their confidence in these conclusions. They provide additional information about the quality of information used and allow traceability to data and resources.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consesus
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

Likelihood				
Very Likely	**Likely**	**As Likely as Not**	**Unlikely**	**Very Unlikely**
≥ 9 in 10	≥ 2 in 3	= 1 in 2	≤ 1 in 3	≤ 1 in 10

Table 1: This table describes the meaning of the various categories of confidence level and likelihood assessment used in NCA4. The levels of confidence are the same as they appear in the CSSR (NCA4 Volume I). And while the likelihood scale is consistent with the CSSR, there are fewer categories, as that report relies more heavily on quantitative methods and statistics. This "binning" of likelihood is consistent with other USGCRP sustained assessment products, such as the Climate and Health Assessment[4] and NCA3.[8]

Glossary of Terms

NCA4 uses the glossary available on the USGCRP website (http://www.globalchange.gov/climate-change/glossary). It was developed for NCA3 and largely draws from the IPCC glossary of terms. Over time, it has been updated with selected new terms from more recent USGCRP assessments, including *The Impacts of Climate Change on Human Health in the United States* (https://health2016.globalchange.gov/glossary-and-acronyms) and the *Climate Science Special Report* (https://science2017.globalchange.gov/chapter/appendix-e/).

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Summary Findings

NCA4 Summary Findings

These Summary Findings represent a high-level synthesis of the material in the underlying report. The findings consolidate Key Messages and supporting evidence from 16 national-level topic chapters, 10 regional chapters, and 2 chapters that focus on societal response strategies (mitigation and adaptation). Unless otherwise noted, qualitative statements regarding future conditions in these Summary Findings are broadly applicable across the range of different levels of future climate change and associated impacts considered in this report.

1. Communities

Climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth.

The impacts of climate change are already being felt in communities across the country. More frequent and intense extreme weather and climate-related events, as well as changes in average climate conditions, are expected to continue to damage infrastructure, ecosystems, and social systems that provide essential benefits to communities. Future climate change is expected to further disrupt many areas of life, exacerbating existing challenges to prosperity posed by aging and deteriorating infrastructure, stressed ecosystems, and economic inequality. Impacts within and across regions will not be distributed equally. People who are already vulnerable, including lower-income and other marginalized communities, have lower capacity to prepare for and cope with extreme weather and climate-related events and are expected to experience greater impacts. Prioritizing adaptation actions for the most vulnerable populations would contribute to a more equitable future within and across communities. Global action to significantly cut greenhouse gas emissions can substantially reduce climate-related risks and increase opportunities for these populations in the longer term.

2. Economy

Without substantial and sustained global mitigation and regional adaptation efforts, climate change is expected to cause growing losses to American infrastructure and property and impede the rate of economic growth over this century.

In the absence of significant global mitigation action and regional adaptation efforts, rising temperatures, sea level rise, and changes in extreme events are expected to increasingly disrupt and damage critical infrastructure and property, labor productivity, and the vitality of our communities. Regional economies and industries that depend on natural resources and favorable climate conditions, such as agriculture, tourism, and fisheries, are vulnerable to the growing impacts of climate change. Rising temperatures are projected to reduce the efficiency of power generation while increasing energy demands, resulting in higher electricity costs. The impacts of climate change beyond our borders are expected to increasingly affect our trade and economy, including import and export prices and U.S. businesses

with overseas operations and supply chains. Some aspects of our economy may see slight near-term improvements in a modestly warmer world. However, the continued warming that is projected to occur without substantial and sustained reductions in global greenhouse gas emissions is expected to cause substantial net damage to the U.S. economy throughout this century, especially in the absence of increased adaptation efforts. With continued growth in emissions at historic rates, annual losses in some economic sectors are projected to reach hundreds of billions of dollars by the end of the century—more than the current gross domestic product (GDP) of many U.S. states.

3. Interconnected Impacts

Climate change affects the natural, built, and social systems we rely on individually and through their connections to one another. These interconnected systems are increasingly vulnerable to cascading impacts that are often difficult to predict, threatening essential services within and beyond the Nation's borders.

Climate change presents added risks to interconnected systems that are already exposed to a range of stressors such as aging and deteriorating infrastructure, land-use changes, and population growth. Extreme weather and climate-related impacts on one system can result in increased risks or failures in other critical systems, including water resources, food production and distribution, energy and transportation, public health, international trade, and national security. The full extent of climate change risks to interconnected systems, many of which span regional and national boundaries, is often greater than the sum of risks to individual sectors. Failure to anticipate interconnected impacts can lead to missed opportunities for effectively managing the risks of climate change and can also lead to management responses that increase risks to other sectors and regions. Joint planning with stakeholders across sectors, regions, and jurisdictions can help identify critical risks arising from interaction among systems ahead of time.

4. Actions to Reduce Risks

Communities, governments, and businesses are working to reduce risks from and costs associated with climate change by taking action to lower greenhouse gas emissions and implement adaptation strategies. While mitigation and adaptation efforts have expanded substantially in the last four years, they do not yet approach the scale considered necessary to avoid substantial damages to the economy, environment, and human health over the coming decades.

Future risks from climate change depend primarily on decisions made today. The integration of climate risk into decision-making and the implementation of adaptation activities have significantly increased since the Third National Climate Assessment in 2014, including in areas of financial risk reporting, capital investment planning, development of engineering standards, military planning, and disaster risk management. Transformations in the energy sector—including the displacement of coal by natural gas and increased deployment of

renewable energy—along with policy actions at the national, regional, state, and local levels are reducing greenhouse gas emissions in the United States. While these adaptation and mitigation measures can help reduce damages in a number of sectors, this assessment shows that more immediate and substantial global greenhouse gas emissions reductions, as well as regional adaptation efforts, would be needed to avoid the most severe consequences in the long term. Mitigation and adaptation actions also present opportunities for additional benefits that are often more immediate and localized, such as improving local air quality and economies through investments in infrastructure. Some benefits, such as restoring ecosystems and increasing community vitality, may be harder to quantify.

5. Water

The quality and quantity of water available for use by people and ecosystems across the country are being affected by climate change, increasing risks and costs to agriculture, energy production, industry, recreation, and the environment.

Rising air and water temperatures and changes in precipitation are intensifying droughts, increasing heavy downpours, reducing snowpack, and causing declines in surface water quality, with varying impacts across regions. Future warming will add to the stress on water supplies and adversely impact the availability of water in parts of the United States. Changes in the relative amounts and timing of snow and rainfall are leading to mismatches between water availability and needs in some regions, posing threats to, for example, the future reliability of hydropower production in the Southwest and the Northwest. Groundwater depletion is exacerbating drought risk in many parts of the United States, particularly in the Southwest and Southern Great Plains. Dependable and safe water supplies for U.S. Caribbean, Hawai'i, and U.S.-Affiliated Pacific Island communities are threatened by drought, flooding, and saltwater contamination due to sea level rise. Most U.S. power plants rely on a steady supply of water for cooling, and operations are expected to be affected by changes in water availability and temperature increases. Aging and deteriorating water infrastructure, typically designed for past environmental conditions, compounds the climate risk faced by society. Water management strategies that account for changing climate conditions can help reduce present and future risks to water security, but implementation of such practices remains limited.

6. Health

Impacts from climate change on extreme weather and climate-related events, air quality, and the transmission of disease through insects and pests, food, and water increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable.

Changes in temperature and precipitation are increasing air quality and health risks from wildfire and ground-level ozone pollution. Rising air and water temperatures and more intense extreme events are expected to increase exposure to waterborne and foodborne diseases, affecting food and water safety. With continued warming, cold-related deaths are

projected to decrease and heat-related deaths are projected to increase; in most regions, increases in heat-related deaths are expected to outpace reductions in cold-related deaths. The frequency and severity of allergic illnesses, including asthma and hay fever, are expected to increase as a result of a changing climate. Climate change is also projected to alter the geographic range and distribution of disease-carrying insects and pests, exposing more people to ticks that carry Lyme disease and mosquitoes that transmit viruses such as Zika, West Nile, and dengue, with varying impacts across regions. Communities in the Southeast, for example, are particularly vulnerable to the combined health impacts from vector-borne disease, heat, and flooding. Extreme weather and climate-related events can have lasting mental health consequences in affected communities, particularly if they result in degradation of livelihoods or community relocation. Populations including older adults, children, low-income communities, and some communities of color are often disproportionately affected by, and less resilient to, the health impacts of climate change. Adaptation and mitigation policies and programs that help individuals, communities, and states prepare for the risks of a changing climate reduce the number of injuries, illnesses, and deaths from climate-related health outcomes.

7. Indigenous Peoples

Climate change increasingly threatens Indigenous communities' livelihoods, economies, health, and cultural identities by disrupting interconnected social, physical, and ecological systems.

Many Indigenous peoples are reliant on natural resources for their economic, cultural, and physical well-being and are often uniquely affected by climate change. The impacts of climate change on water, land, coastal areas, and other natural resources, as well as infrastructure and related services, are expected to increasingly disrupt Indigenous peoples' livelihoods and economies, including agriculture and agroforestry, fishing, recreation, and tourism. Adverse impacts on subsistence activities have already been observed. As climate changes continue, adverse impacts on culturally significant species and resources are expected to result in negative physical and mental health effects. Throughout the United States, climate-related impacts are causing some Indigenous peoples to consider or actively pursue community relocation as an adaptation strategy, presenting challenges associated with maintaining cultural and community continuity. While economic, political, and infrastructure limitations may affect these communities' ability to adapt, tightly knit social and cultural networks present opportunities to build community capacity and increase resilience. Many Indigenous peoples are taking steps to adapt to climate change impacts structured around self-determination and traditional knowledge, and some tribes are pursuing mitigation actions through development of renewable energy on tribal lands.

8. Ecosystems and Ecosystem Services

Ecosystems and the benefits they provide to society are being altered by climate change, and these impacts are projected to continue. Without substantial and sustained reductions in global greenhouse gas emissions, transformative impacts on some ecosystems will occur; some coral reef and sea ice ecosystems are already experiencing such transformational changes.

Many benefits provided by ecosystems and the environment, such as clean air and water, protection from coastal flooding, wood and fiber, crop pollination, hunting and fishing, tourism, cultural identities, and more will continue to be degraded by the impacts of climate change. Increasing wildfire frequency, changes in insect and disease outbreaks, and other stressors are expected to decrease the ability of U.S. forests to support economic activity, recreation, and subsistence activities. Climate change has already had observable impacts on biodiversity, ecosystems, and the benefits they provide to society. These impacts include the migration of native species to new areas and the spread of invasive species. Such changes are projected to continue, and without substantial and sustained reductions in global greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided in the long term. Valued aspects of regional heritage and quality of life tied to ecosystems, wildlife, and outdoor recreation will change with the climate, and as a result, future generations can expect to experience and interact with the natural environment in ways that are different from today. Adaptation strategies, including prescribed burning to reduce fuel for wildfire, creation of safe havens for important species, and control of invasive species, are being implemented to address emerging impacts of climate change. While some targeted response actions are underway, many impacts, including losses of unique coral reef and sea ice ecosystems, can only be avoided by significantly reducing global emissions of carbon dioxide and other greenhouse gases.

9. Agriculture and Food

Rising temperatures, extreme heat, drought, wildfire on rangelands, and heavy downpours are expected to increasingly disrupt agricultural productivity in the United States. Expected increases in challenges to livestock health, declines in crop yields and quality, and changes in extreme events in the United States and abroad threaten rural livelihoods, sustainable food security, and price stability.

Climate change presents numerous challenges to sustaining and enhancing crop productivity, livestock health, and the economic vitality of rural communities. While some regions (such as the Northern Great Plains) may see conditions conducive to expanded or alternative crop productivity over the next few decades, overall, yields from major U.S. crops are expected to decline as a consequence of increases in temperatures and possibly changes in water availability, soil erosion, and disease and pest outbreaks. Increases in temperatures during the growing season in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture. Projected increases in extreme heat conditions are expected to lead to further heat stress for livestock, which can result in large economic

losses for producers. Climate change is also expected to lead to large-scale shifts in the availability and prices of many agricultural products across the world, with corresponding impacts on U.S. agricultural producers and the U.S. economy. These changes threaten future gains in commodity crop production and put rural livelihoods at risk. Numerous adaptation strategies are available to cope with adverse impacts of climate variability and change on agricultural production. These include altering what is produced, modifying the inputs used for production, adopting new technologies, and adjusting management strategies. However, these strategies have limits under severe climate change impacts and would require sufficient long- and short-term investment in changing practices.

10. Infrastructure

Our Nation's aging and deteriorating infrastructure is further stressed by increases in heavy precipitation events, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average precipitation and temperature. Without adaptation, climate change will continue to degrade infrastructure performance over the rest of the century, with the potential for cascading impacts that threaten our economy, national security, essential services, and health and well-being.

Climate change and extreme weather events are expected to increasingly disrupt our Nation's energy and transportation systems, threatening more frequent and longer-lasting power outages, fuel shortages, and service disruptions, with cascading impacts on other critical sectors. Infrastructure currently designed for historical climate conditions is more vulnerable to future weather extremes and climate change. The continued increase in the frequency and extent of high-tide flooding due to sea level rise threatens America's trillion-dollar coastal property market and public infrastructure, with cascading impacts to the larger economy. In Alaska, rising temperatures and erosion are causing damage to buildings and coastal infrastructure that will be costly to repair or replace, particularly in rural areas; these impacts are expected to grow without adaptation. Expected increases in the severity and frequency of heavy precipitation events will affect inland infrastructure in every region, including access to roads, the viability of bridges, and the safety of pipelines. Flooding from heavy rainfall, storm surge, and rising high tides is expected to compound existing issues with aging infrastructure in the Northeast. Increased drought risk will threaten oil and gas drilling and refining, as well as electricity generation from power plants that rely on surface water for cooling. Forward-looking infrastructure design, planning, and operational measures and standards can reduce exposure and vulnerability to the impacts of climate change and reduce energy use while providing additional near-term benefits, including reductions in greenhouse gas emissions.

11. Oceans and Coasts

Coastal communities and the ecosystems that support them are increasingly threatened by the impacts of climate change. Without significant reductions in global greenhouse gas emissions and regional adaptation measures, many coastal regions will be transformed by the latter part of this century, with impacts affecting other regions and sectors. Even in a future with lower greenhouse gas emissions, many communities are expected to suffer financial impacts as chronic high-tide flooding leads to higher costs and lower property values.

Rising water temperatures, ocean acidification, retreating arctic sea ice, sea level rise, high-tide flooding, coastal erosion, higher storm surge, and heavier precipitation events threaten our oceans and coasts. These effects are projected to continue, putting ocean and marine species at risk, decreasing the productivity of certain fisheries, and threatening communities that rely on marine ecosystems for livelihoods and recreation, with particular impacts on fishing communities in Hawai'i and the U.S.-Affiliated Pacific Islands, the U.S. Caribbean, and the Gulf of Mexico. Lasting damage to coastal property and infrastructure driven by sea level rise and storm surge is expected to lead to financial losses for individuals, businesses, and communities, with the Atlantic and Gulf Coasts facing above-average risks. Impacts on coastal energy and transportation infrastructure driven by sea level rise and storm surge have the potential for cascading costs and disruptions across the country. Even if significant emissions reductions occur, many of the effects from sea level rise over this century—and particularly through mid-century—are already locked in due to historical emissions, and many communities are already dealing with the consequences. Actions to plan for and adapt to more frequent, widespread, and severe coastal flooding, such as shoreline protection and conservation of coastal ecosystems, would decrease direct losses and cascading impacts on other sectors and parts of the country. More than half of the damages to coastal property are estimated to be avoidable through well-timed adaptation measures. Substantial and sustained reductions in global greenhouse gas emissions would also significantly reduce projected risks to fisheries and communities that rely on them.

12. Tourism and Recreation

Outdoor recreation, tourist economies, and quality of life are reliant on benefits provided by our natural environment that will be degraded by the impacts of climate change in many ways.

Climate change poses risks to seasonal and outdoor economies in communities across the United States, including impacts on economies centered around coral reef-based recreation, winter recreation, and inland water-based recreation. In turn, this affects the well-being of the people who make their living supporting these economies, including rural, coastal, and Indigenous communities. Projected increases in wildfire smoke events are expected to impair outdoor recreational activities and visibility in wilderness areas. Declines in snow and ice cover caused by warmer winter temperatures are expected to negatively impact the winter recreation industry in the Northwest, Northern Great Plains, and the Northeast. Some fish, birds, and mammals are expected to shift where they live as a result of climate change,

with implications for hunting, fishing, and other wildlife-related activities. These and other climate-related impacts are expected to result in decreased tourism revenue in some places and, for some communities, loss of identity. While some new opportunities may emerge from these ecosystem changes, cultural identities and economic and recreational opportunities based around historical use of and interaction with species or natural resources in many areas are at risk. Proactive management strategies, such as the use of projected stream temperatures to set priorities for fish conservation, can help reduce disruptions to tourist economies and recreation.

Overview

1 Overview

Howe Ridge Fire in Montana's Glacier National Park on August 12, 2018. *Photo credit: National Park Service.*

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Introduction

Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities. The impacts of global climate change are already being felt in the United States and are projected to intensify in the future—but the severity of future impacts will depend largely on actions taken to reduce greenhouse gas emissions and to adapt to the changes that will occur. Americans increasingly recognize the risks climate change poses to their everyday lives and livelihoods and are beginning to respond (Figure 1.1). Water managers in the Colorado River Basin have mobilized users to conserve water in response to ongoing drought intensified by higher temperatures, and an extension program in Nebraska is helping ranchers reduce drought and heat risks to their operations. The state of Hawai'i is developing management options to promote coral reef recovery from widespread bleaching events caused by warmer waters that threaten tourism, fisheries, and coastal protection from wind and waves. To address higher risks of flooding from heavy rainfall, local governments in southern Louisiana are pooling hazard reduction funds, and cities and states in the Northeast are investing in more resilient water, energy, and transportation infrastructure. In Alaska, a tribal health organization is developing adaptation strategies to address physical and mental health challenges driven by climate change and other environmental changes. As Midwestern farmers adopt new management strategies to reduce erosion and nutrient losses caused by heavier rains, forest managers in the Northwest are developing adaptation strategies in response to wildfire increases that affect human health, water resources, timber production, fish and wildlife, and recreation. After extensive hurricane damage fueled in part by a warmer atmosphere and warmer, higher seas, communities in Texas are considering ways to rebuild more resilient infrastructure. In the U.S. Caribbean, governments are developing new frameworks for storm recovery based on lessons learned from the 2017 hurricane season.

Climate-related risks will continue to grow without additional action. Decisions made today determine risk exposure for current and future generations and will either broaden or limit options to reduce the negative consequences of climate change. While Americans are responding in ways that can bolster resilience and improve livelihoods, neither global efforts to mitigate the causes of climate change nor regional efforts to adapt to the impacts currently approach the scales needed to avoid substantial damages to the U.S. economy, environment, and human health and well-being over the coming decades.

Americans Respond to the Impacts of Climate Change

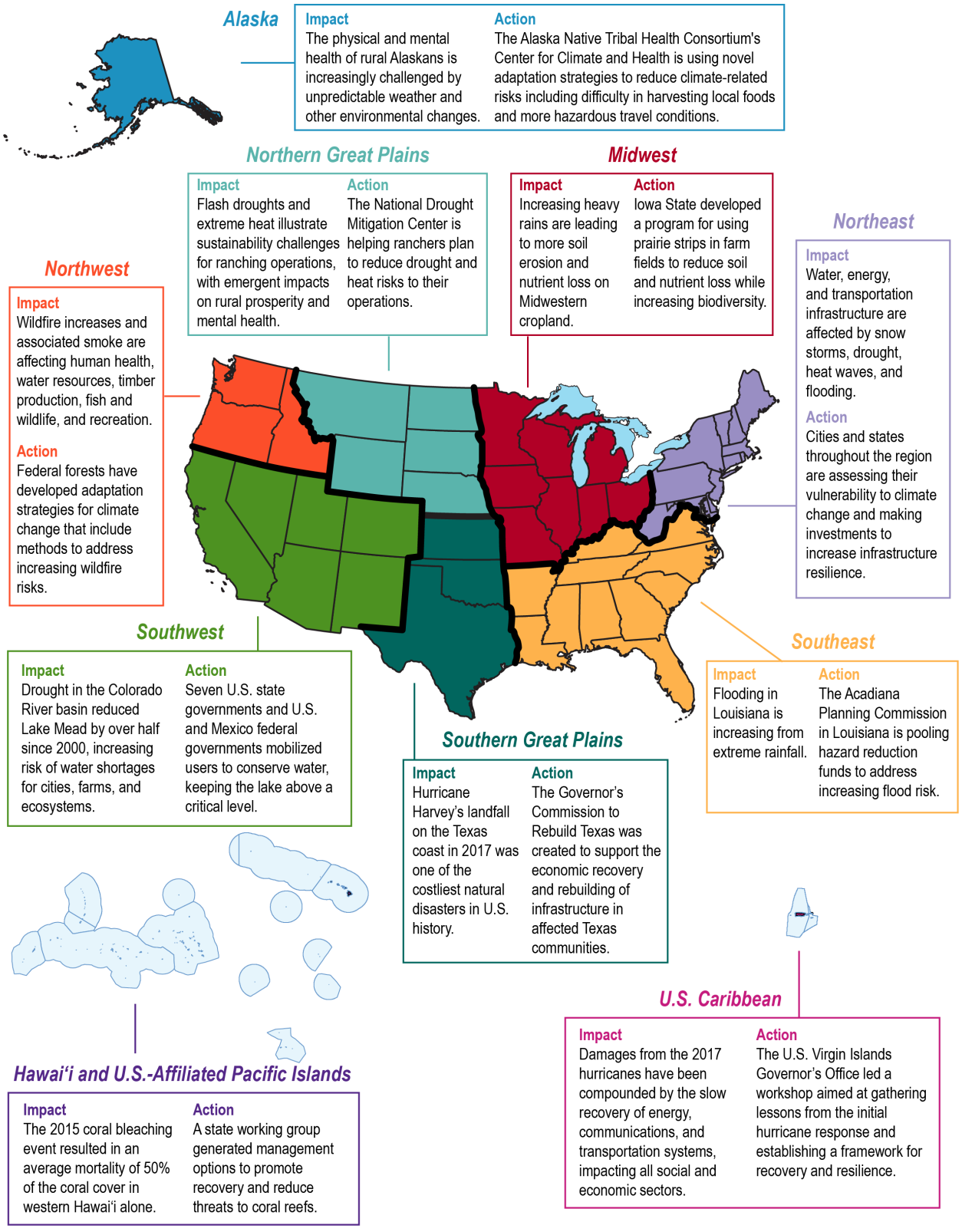


Figure 1.1: This map shows climate-related impacts that have occurred in each region since the Third National Climate Assessment in 2014 and response actions that are helping the region address related risks and costs. These examples are illustrative; they are not indicative of which impact is most significant in each region or which response action might be most effective. *Source: NCA4 Regional Chapters.*

Climate shapes where and how we live and the environment around us. Natural ecosystems, agricultural systems, water resources, and the benefits they provide to society are adapted to past climate conditions and their natural range of variability. A water manager may use past or current streamflow records to design a dam, a city could issue permits for coastal development based on current flood maps, and an electric utility or a farmer may invest in equipment suited to the current climate, all with the expectation that their investments and management practices will meet future needs.

However, the assumption that current and future climate conditions will resemble the recent past is no longer valid (Ch. 28: Adaptation, KM 2). Observations collected around the world provide significant, clear, and compelling evidence that global average temperature is much higher, and is rising more rapidly, than anything modern civilization has experienced, with widespread and growing impacts (Figure 1.2) (CSSR, Ch. 1.9). The warming trend observed over the past century can only be explained by the effects that human activities, especially emissions of greenhouse gases, have had on the climate (Ch. 2: Climate, KM 1 and Figure 2.1).

Climate change is transforming where and how we live and presents growing challenges to human health and quality of life, the economy, and the natural systems that support us. Risks posed by climate variability and change vary by region and sector and by the vulnerability of people experiencing impacts. Social, economic, and geographic factors shape the exposure of people and communities to climate-related impacts and their capacity to respond. Risks are often highest for those that are already vulnerable, including low-income communities, some communities of color, children, and the elderly (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, KM 1–3; Ch. 28: Adaptation, Introduction). Climate change threatens to exacerbate existing social and economic inequalities that result in higher exposure and sensitivity to extreme weather and climate-related events and other changes (Ch. 11: Urban, KM 1). Marginalized populations may also be affected disproportionately by actions to address the underlying causes and impacts of climate change, if they are not implemented under policies that consider existing inequalities (Ch. 11: Urban, KM 4; Ch. 28: Adaptation, KM 4).

This report draws a direct connection between the warming atmosphere and the resulting changes that affect Americans' lives, communities, and livelihoods, now and in the future. It documents vulnerabilities, risks, and impacts associated with natural climate variability and human-caused climate change across the United States and provides examples of response actions underway in many communities. It concludes that *the evidence of human-caused climate change is overwhelming and continues to strengthen, that the impacts of climate change are intensifying across the country, and that climate-related threats to Americans' physical, social, and economic well-being are rising.* These impacts are projected to intensify—but how much they intensify will depend on actions taken to reduce global greenhouse gas emissions and to adapt to the risks from climate change now and in the coming decades (Ch. 28: Adaptation, Introduction; Ch. 29: Mitigation, KM 3 and 4).

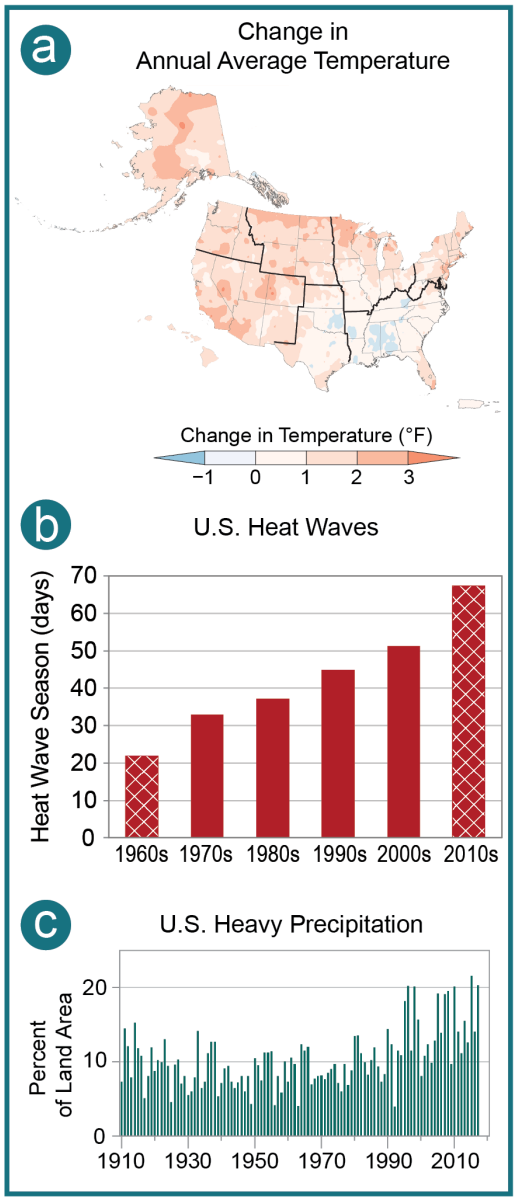
Our Changing Climate: Observations, Causes, and Future Change

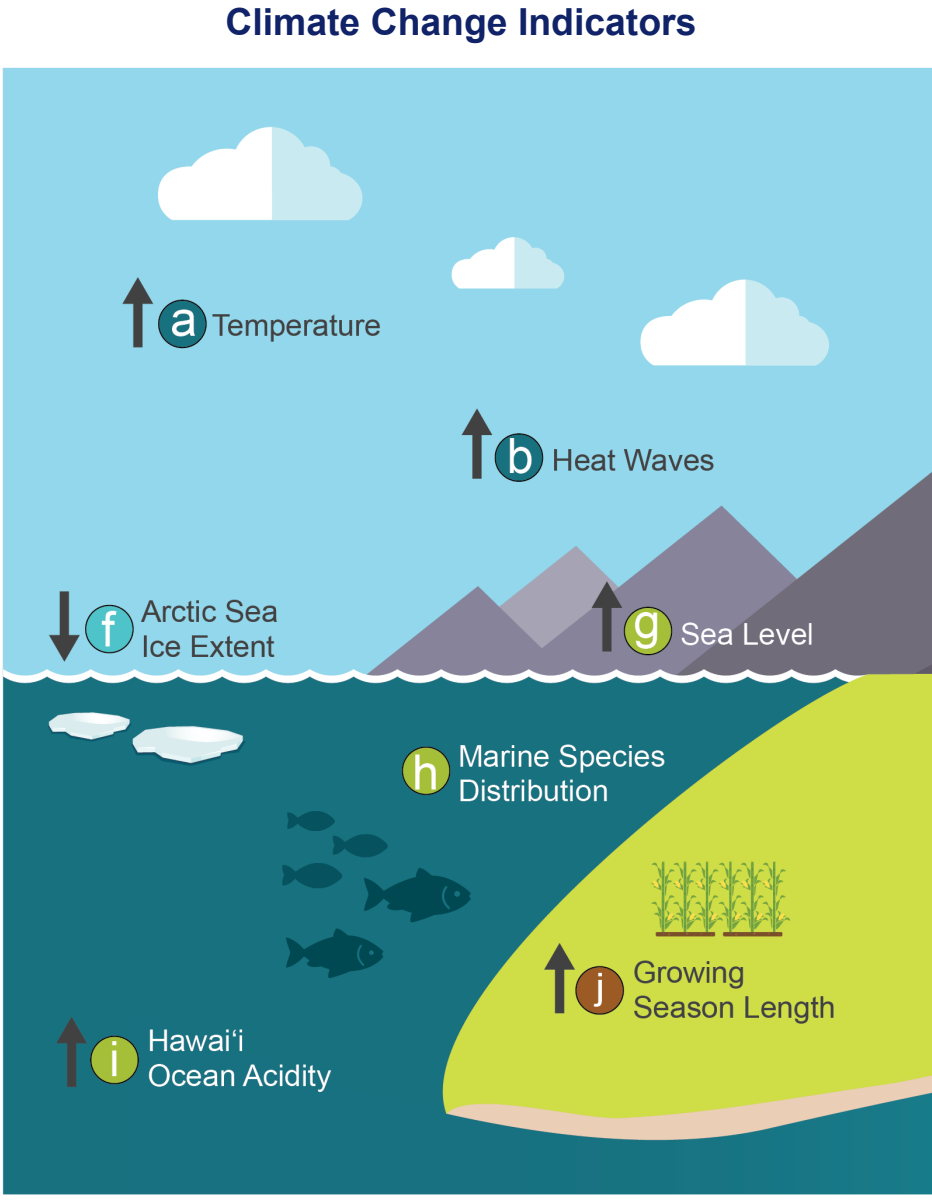
Observed Change

Observations from around the world show the widespread effects of increasing greenhouse gas concentrations on Earth's climate. High temperature extremes and heavy precipitation events are increasing. Glaciers and snow cover are shrinking, and sea ice is retreating. Seas are warming, rising, and becoming more acidic, and marine species are moving to new locations toward cooler waters. Flooding is becoming more frequent along the U.S. coastline. Growing seasons are lengthening, and wildfires are increasing. These and many other changes are clear signs of a warming world (Figure 1.2) (Ch. 2: Climate, Box 2.2; App. 3: Data & Scenarios, see also the USGCRP Indicators and EPA Indicators websites).

California Drought Affects Mountain Snowpack

California's recent multiyear drought left Tioga Pass in the Sierra Nevada mountain range nearly snowless at the height of winter in January 2015. *Photo credit: Bartshé Miller.*





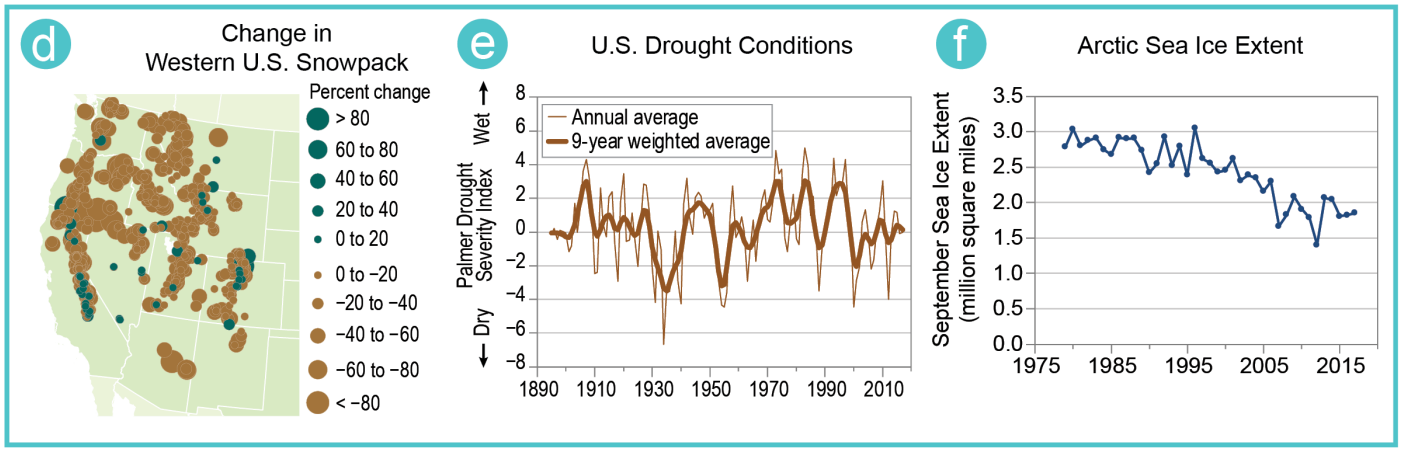
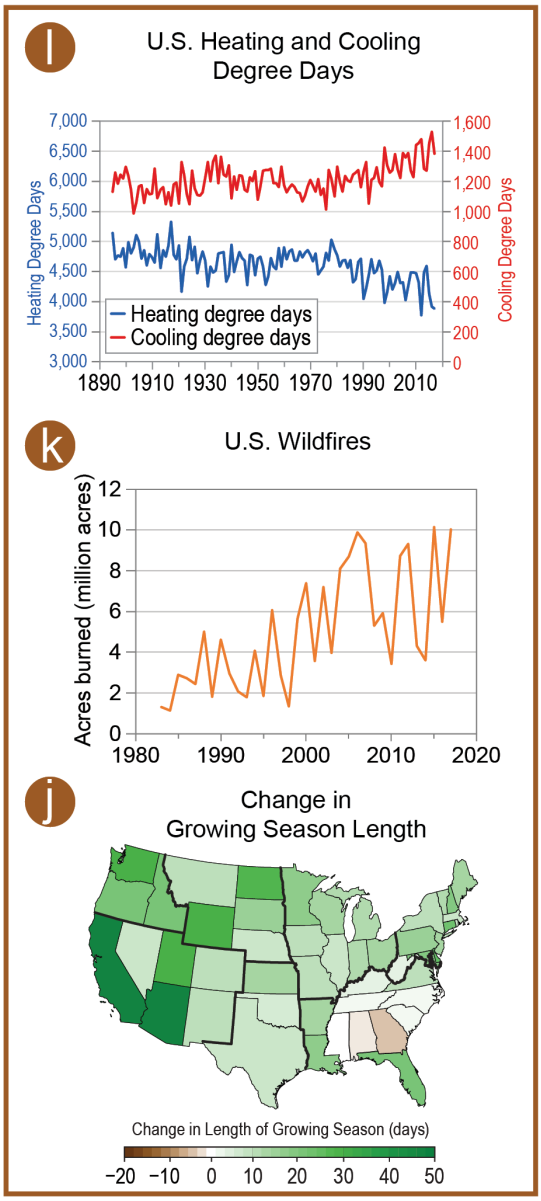
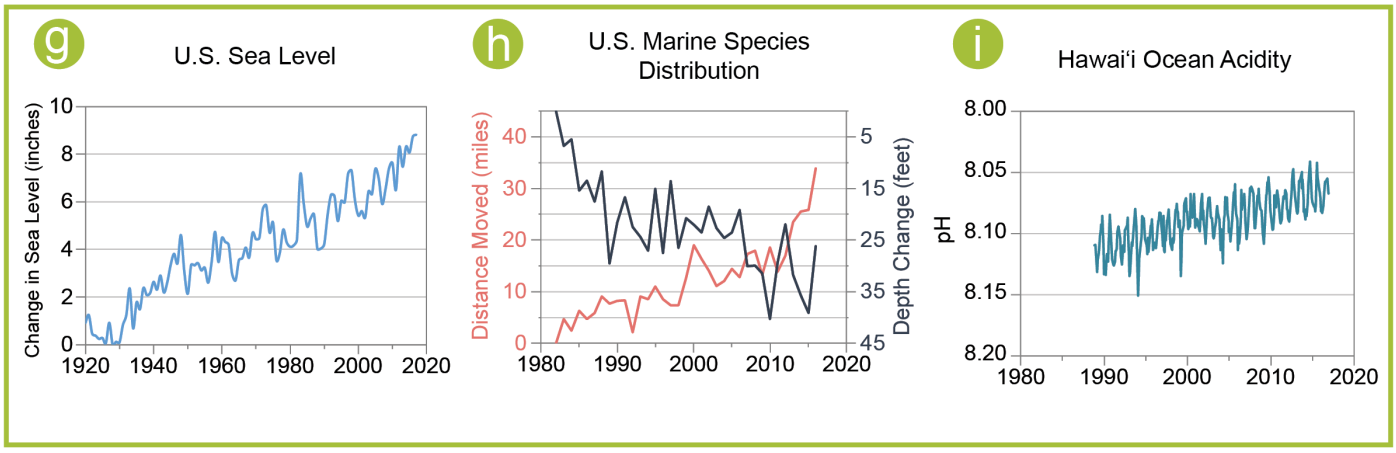


Figure 1.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change





based on data collected across the United States. Upward-pointing arrows indicate an increasing trend; downward-pointing arrows indicate a decreasing trend. Bidirectional arrows (e.g., for drought conditions) indicate a lack of a definitive national trend.

(Figure caption continued on next page)

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

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

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

Land and ecosystems (j–l): (j) The average length of the growing season has increased across the contiguous United States since the early 20th century, meaning that, on average, the last spring frost occurs earlier and the first fall frost arrives later; this map shows changes in growing season length at the state level from 1895 to 2016. (k) Warmer and drier conditions have contributed to an increase in large forest fires in the western United States and Interior Alaska over the past several decades (CSSR, Ch. 8.3). (l) Degree days are defined as the number of degrees by which the average daily temperature is higher than 65°F (cooling degree days) or lower than 65°F (heating degree days) and are used as a proxy for energy demands for cooling or heating buildings. Changes in temperatures indicate that heating needs have decreased and cooling needs have increased in the contiguous United States over the past century.

Sources: (a) adapted from Vose et al. 2017, (b) EPA, (c–f and h–l) adapted from EPA 2016, (g and center infographic) EPA and NOAA.

Causes of Change

Scientists have understood the fundamental physics of climate change for almost 200 years. In the 1850s, researchers demonstrated that carbon dioxide and other naturally occurring greenhouse gases in the atmosphere prevent some of the heat radiating from Earth's surface from escaping to space: this is known as the greenhouse effect. This natural greenhouse effect warms the planet's surface about 60°F above what it would be otherwise, creating a habitat suitable for life. Since the late 19th century, however, humans have released an increasing amount of greenhouse gases into the atmosphere through burning fossil fuels and, to a lesser extent, deforestation and land-use change. As a result, the atmospheric concentration of carbon dioxide, the largest contributor to human-caused warming, has increased by about 40% over the industrial era. This change has intensified the natural greenhouse effect, driving an increase in global surface temperatures and other widespread changes in Earth's climate that are unprecedented in the history of modern civilization.

Global climate is also influenced by natural factors that determine how much of the sun's energy enters and leaves Earth's atmosphere and by natural climate cycles that affect temperatures and weather patterns in the short term, especially regionally (see Ch. 2: Climate, Box 2.1). However, the unambiguous long-term warming trend in global average temperature over the last century cannot be explained by natural factors alone. Greenhouse gas emissions from human activities are the

only factors that can account for the observed warming over the last century; there are no credible alternative human or natural explanations supported by the observational evidence. Without human activities, the influence of natural factors alone would actually have had a slight cooling effect on global climate over the last 50 years (Ch. 2: Climate, KM 1, Figure 2.1).

Future Change

Greenhouse gas emissions from human activities will continue to affect Earth's climate for decades and even centuries. Humans are adding carbon dioxide to the atmosphere at a rate far greater than it is removed by natural processes, creating a long-lived reservoir of the gas in the atmosphere and oceans that is driving the climate to a warmer and warmer state. Some of the other greenhouse gases released by human activities, such as methane, are removed from the atmosphere by natural processes more quickly than carbon dioxide; as a result, efforts to cut emissions of these gases could help reduce the rate of global temperature increases over the next few decades. However, longer-term changes in climate will largely be determined by emissions and atmospheric concentrations of carbon dioxide and other longer-lived greenhouse gases (Ch. 2: Climate, KM 2).

Climate models representing our understanding of historical and current climate conditions are often used to project how our world will change under future conditions (see Ch. 2: Climate, Box 2.7). "Climate" is defined as weather conditions over multiple decades, and climate model projections are generally not designed to capture annual or even decadal variation in climate conditions. Instead, projections are typically used to capture long-term changes, such as how the climate system will respond to changes in greenhouse gas levels over this century. Scientists test climate models by comparing them to current observations and historical changes. Confidence in these models is based, in part, on how well they reproduce these observed changes. Climate models have proven remarkably accurate in simulating the climate change we have experienced to date, particularly in the past 60 years or so when we have greater confidence in observations (see CSSR, Ch. 4.3.1). The observed signals of a changing climate continue to become stronger and clearer over time, giving scientists increased confidence in their findings even since the Third National Climate Assessment was released in 2014.

Today, the largest uncertainty in projecting future climate conditions is the level of greenhouse gas emissions going forward. Future global greenhouse gas emissions levels and resulting impacts depend on economic, political, and demographic factors that can be difficult to predict with confidence far into the future. Like previous climate assessments, NCA4 relies on a suite of possible scenarios to evaluate the implications of different climate outcomes and associated impacts throughout the 21st century. These "Representative Concentration Pathways" (RCPs) capture a range of potential greenhouse gas emissions pathways and associated atmospheric concentration levels through 2100.

RCPs drive climate model projections for temperature, precipitation, sea level, and other variables under futures that have either lower or higher greenhouse gas emissions. RCPs are numbered according to changes in radiative forcing by 2100 relative to preindustrial conditions: +2.6, +4.5, +6.0, or +8.5 watts per square meter (W/m^2). Each RCP leads to a different

Box 1.1: Confidence and Uncertainty in Climate Science

Many of the decisions we make every day are based on less-than-perfect knowledge. For example, while GPS-based applications on smartphones can provide a travel-time estimate for our daily drive to work, an unexpected factor like a sudden downpour or fender bender might mean a ride originally estimated to be 20 minutes could actually take longer. Fortunately, even with this uncertainty we are confident that our trip is unlikely to take less than 20 minutes or more than half an hour—and we know where we are headed. We have enough information to plan our commute.

Uncertainty is also a part of science. A key goal of scientific research is to increase our confidence and reduce the uncertainty in our understanding of the world around us. Even so, there is no expectation that uncertainty can be fully eliminated, just as we do not expect a perfectly accurate estimate for our drive time each day. Studying Earth's climate system is particularly challenging because it integrates many aspects of a complex natural system as well as many human-made systems. Climate scientists find varying ranges of uncertainty in many areas, including observations of climate variables, the analysis and interpretation of those measurements, the development of new observational instruments, and the use of computer-based models of the processes governing Earth's climate system. While there is inherent uncertainty in climate science, there is high confidence in our understanding of the greenhouse effect and the knowledge that human activities are changing the climate in unprecedented ways. There is enough information to make decisions based on that understanding.

Where important uncertainties do exist, efforts to quantify and report those uncertainties can help decision-makers plan for a range of possible future outcomes. These efforts also help scientists advance understanding and ultimately increase confidence in and the usefulness of model projections. Assessments like this one explicitly address scientific uncertainty associated with findings and use specific language to express it to improve relevance to risk analysis and decision-making (see Front Matter and Box 1.2).

level of projected global temperature change; higher numbers indicate greater projected temperature change and associated impacts. The higher scenario (RCP8.5) represents a future where annual greenhouse gas emissions increase significantly throughout the 21st century before leveling off by 2100, whereas the other RCPs represent more rapid and substantial mitigation by mid-century, with greater reductions thereafter. Current trends in annual greenhouse gas emissions, globally, are consistent with RCP8.5.

Of the two RCPs predominantly referenced throughout this report, the lower scenario (RCP4.5) envisions about 85% lower greenhouse gas emissions than the higher scenario (RCP8.5) by the end of the 21st century (see Ch. 2: Climate, Figure 2.2). In some cases, throughout this report, a very low scenario (RCP2.6) that represents more immediate, substantial, and sustained emissions reductions is considered. Each RCP could be consistent with a range of underlying socioeconomic conditions or policy choices. See the Scenario Products section of Appendix 3 in this report, as well as CSSR Chapters 4.2.1 and 10.2.1 for more detail.

The effects of different future greenhouse gas emissions levels on global climate become most evident around 2050, when temperature (Figure 1.3) (Ch. 2: Climate, Figure 2.2), precipitation,

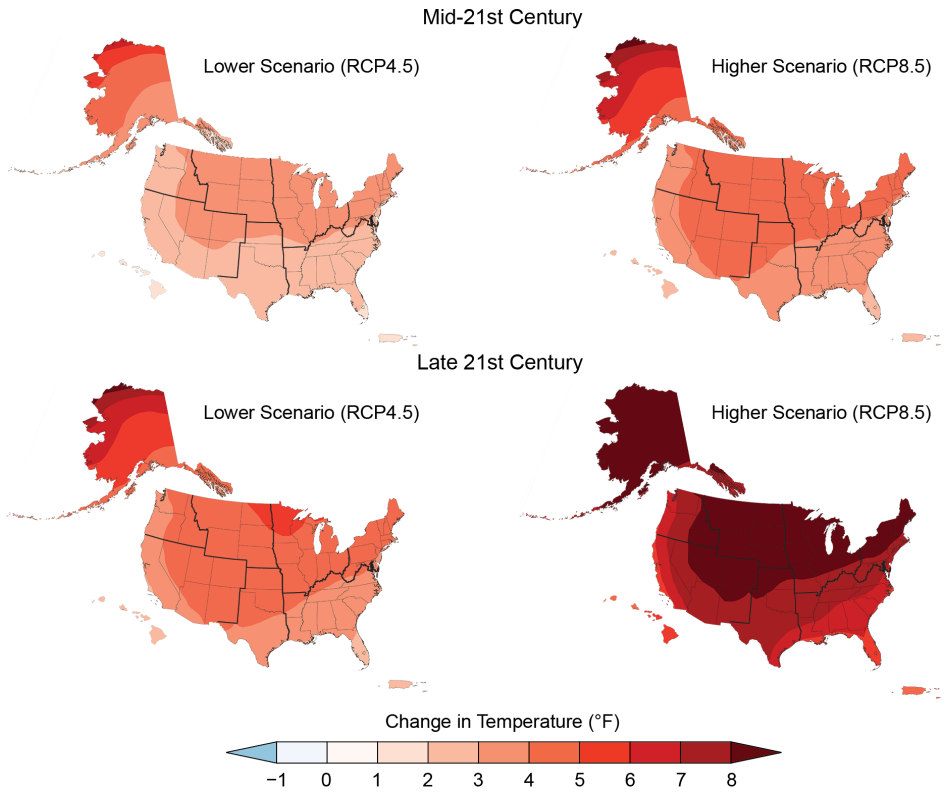


Figure 1.3: Annual average temperatures across the United States are projected to increase over this century, with greater changes at higher latitudes as compared to lower latitudes, and under a higher scenario (RCP8.5; right) than under a lower one (RCP4.5; left). This figure shows projected differences in annual average temperatures for mid-century (2036–2065; top) and end of century (2071–2100; bottom) relative to the near present (1986–2015). *From Figure 2.4, Ch. 2: Climate (Source: adapted from Vose et al. 2017).*

and sea level rise (Figure 1.4) (Ch. 2: Climate, Figure 2.3) projections based on each scenario begin to diverge significantly. With substantial and sustained reductions in greenhouse gas emissions (e.g., consistent with the very low scenario [RCP2.6]), the increase in global annual average temperature relative to preindustrial times could be limited to less than 3.6°F (2°C) (Ch. 2: Climate, Box 2.4; CSSR, Ch. 4.2.1). Without significant greenhouse gas mitigation, the increase in global annual average temperature could reach 9°F or more by the end of this century (Ch. 2: Climate, KM 2). For some aspects of Earth's climate system that take longer to respond to changes in atmospheric greenhouse gas concentrations, such as global sea level, some degree of long-term change will be locked in for centuries to come, regardless of the future scenario (see CSSR, Ch. 12.5.3). Early greenhouse gas emissions mitigation can reduce climate impacts in the nearer term (such as reducing the loss of arctic sea ice and the effects on species that use it) and in the longer term by avoiding critical thresholds (such as marine ice sheet instability and the resulting consequences for global sea level and coastal development; Ch. 29: Mitigation, Timing and Magnitude of Action).

Annual average temperatures in the United States are projected to continue to increase in the coming decades. Regardless of future scenario, additional increases in temperatures across the contiguous United States of at least

Projected Relative Sea Level Change in the United States by 2100

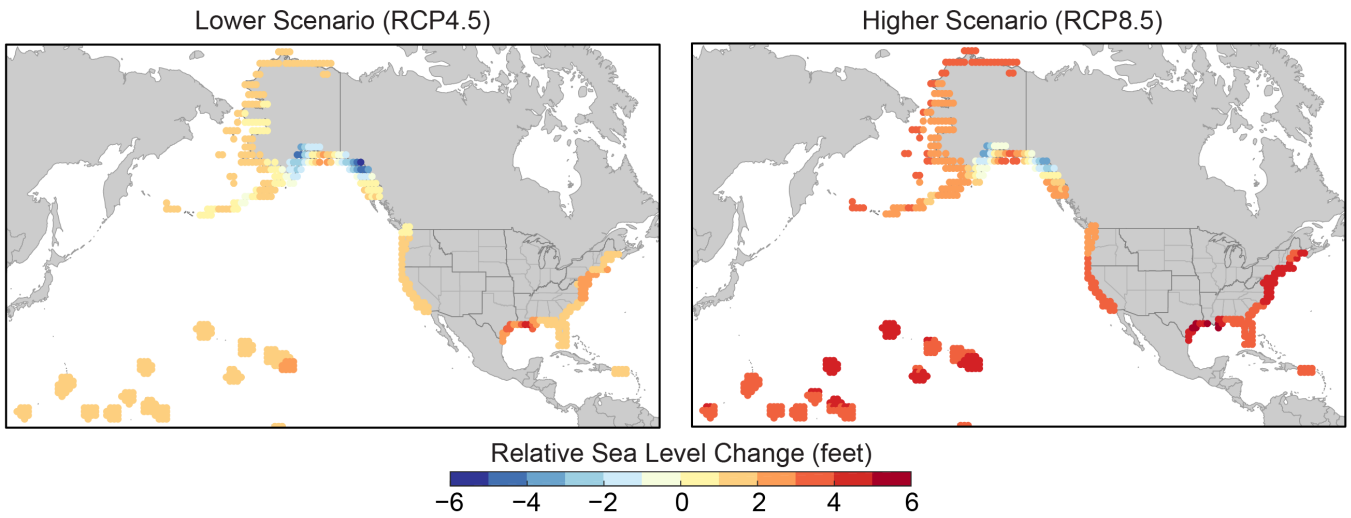


Figure 1.4: The maps show projections of change in relative sea level along the U.S. coast by 2100 (as compared to 2000) under the lower (RCP4.5) and higher (RCP8.5) scenarios (see CSSR, Ch. 12.5). Globally, sea levels will continue to rise from thermal expansion of the ocean and melting of land-based ice masses (such as Greenland, Antarctica, and mountain glaciers). Regionally, however, the amount of sea level rise will not be the same everywhere. Where land is sinking (as along the Gulf of Mexico coastline), relative sea level rise will be higher, and where land is rising (as in parts of Alaska), relative sea level rise will be lower. Changes in ocean circulation (such as the Gulf Stream) and gravity effects due to ice melt will also alter the heights of the ocean regionally. Sea levels are expected to continue to rise along almost all U.S. coastlines, and by 2100, under the higher scenario, coastal flood heights that today cause major damages to infrastructure would become common during high tides nationwide (Ch. 8: Coastal; Scenario Products section in Appendix 3). *Source: adapted from CSSR, Figure 12.4.*

2.3°F relative to 1986–2015 are expected by the middle of this century. As a result, recent record-setting hot years are expected to become common in the near future. By late this century, increases of 2.3°–6.7°F are expected under a lower scenario (RCP4.5) and 5.4°–11.0°F under a higher scenario (RCP8.5) relative to 1986–2015 (Figure 1.3) (Ch. 2: Climate, KM 5, Figure 2.4). Alaska has warmed twice as fast as the global average since the mid-20th century; this trend is expected to continue (Ch. 26: Alaska, Background).

High temperature extremes, heavy precipitation events, high tide flooding events along the U.S. coastline, ocean acidification and warming, and forest fires in the western United States and Alaska are all projected to continue to increase, while land and sea ice cover, snowpack, and surface soil moisture are expected to continue to decline in the coming decades. These and other changes are expected to increasingly impact water resources, air quality, human health, agriculture, natural ecosystems, energy and transportation infrastructure, and many other natural and human systems that support communities across the country. The severity of these projected impacts, and the risks they present to society, is greater under futures with higher greenhouse gas emissions, especially if limited or no adaptation occurs (Ch. 29: Mitigation, KM 2).

Box 1.2: Evaluating Risks to Inform Decisions

In this report, *risks* are often defined in a qualitative sense as threats to life, health and safety, the environment, economic well-being, and other things of value to society (Ch. 28: Adaptation, Introduction). In some cases, risks are described in quantitative terms: estimates of how likely a given threat is to occur (probability) and the damages that would result if it did happen (consequences). Climate change is a risk management challenge for society; it presents uncertain—and potentially severe—consequences for natural and human systems across generations. It is characterized by multiple intersecting and uncertain future hazards and, therefore, acts as a risk multiplier that interacts with other stressors to create new risks or to alter existing ones (see Ch. 17: Complex Systems, KM 1).

Current and future greenhouse gas emissions, and thus mitigation actions to reduce emissions, will largely determine future climate change impacts and risks to society. Mitigation and adaptation activities can be considered complementary strategies—mitigation efforts can reduce future risks, while adaptation can minimize the consequences of changes that are already happening as a result of past and present greenhouse gas emissions. Adaptation entails proactive decision-making and investments by individuals, businesses, and governments to counter specific risks from climate change that vary from place to place. Climate risk management includes some familiar attributes and tactics for most businesses and local governments, which often manage or design for a variety of weather-related risks, including coastal and inland storms, heat waves, threats to water availability, droughts, and floods.

Measuring risk encompasses both likelihoods and consequences of specific outcomes and involves judgments about what is of value, ranking of priorities, and cost–benefit analyses that incorporate the tradeoffs among climate and non-climate related options. This report characterizes specific risks across regions and sectors in an effort to help people assess the risks they face, create and implement a response plan, and monitor and evaluate the efficacy of a given action (see Ch. 28: Adaptation, KM 1, Figure 28.1).

Climate Change in the United States: Current and Future Risks

Some climate-related impacts, such as increasing health risks from extreme heat, are common to many regions of the United States (Ch. 14: Human Health, KM 1). Others represent more localized risks, such as infrastructure damage caused by thawing of permafrost (long-frozen ground) in Alaska or threats to coral reef ecosystems from warmer and more acidic seas in the U.S. Caribbean, as well as Hawai‘i and the U.S.-Affiliated Pacific Islands (Ch. 26: Alaska, KM 2; Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4). Risks vary by both a community's exposure to physical climate impacts and by factors that influence its ability to respond to changing conditions and to recover from adverse weather and climate-related events such as extreme storms or wildfires (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, State of the Sector, KM 1 and 2; Ch. 28: Adaptation, KM 4).

Many places are subject to more than one climate-related impact, such as extreme rainfall combined with coastal flooding, or drought coupled with extreme heat, wildfire, and flooding. The compounding effects of these impacts result in increased risks to people, infrastructure, and interconnected economic sectors (Ch. 11: Urban, KM 1). Impacts affecting

interconnected systems can cascade across sectors and regions, creating complex risks and management challenges. For example, changes in the frequency, intensity, extent, and duration of wildfires can result in a higher instance of landslides that disrupt transportation systems and the flow of goods and services within or across regions (Box 1.3). Many observed impacts reveal vulnerabilities in these interconnected systems that are expected to be exacerbated as climate-related risks intensify. Under a higher scenario (RCP8.5), it is very likely that some impacts, such as the effects of ice sheet disintegration on sea level rise and coastal development, will be irreversible for many thousands of years, and others, such as species extinction, will be permanent (Ch. 7: Ecosystems, KM 1; Ch. 9: Oceans, KM 1; Ch. 29: Mitigation, KM 2).

Economy and Infrastructure

Without more significant global greenhouse gas mitigation and regional adaptation efforts, climate change is expected to cause substantial losses to infrastructure and property and impede the rate of economic growth over this century (Ch. 4: Energy, KM 1; Ch. 8: Coastal, KM 1; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1; Regional Chapters 18–27). Regional economies and industries that depend on natural resources and favorable climate conditions, such as agriculture, tourism, and fisheries, are increasingly vulnerable to impacts driven by climate change (Ch. 7: Ecosystems, KM 3; Ch. 10: Agriculture, KM 1). Reliable and affordable energy supplies, which underpin virtually every sector of the economy, are increasingly at risk from climate change and weather extremes (Ch. 4: Energy, KM 1). The impacts of climate

Box 1.3: Interconnected Impacts of Climate Change

The impacts of climate change and extreme weather on natural and built systems are often considered from the perspective of individual sectors: how does a changing climate impact water resources, the electric grid, or the food system? None of these sectors, however, exists in isolation. The natural, built, and social systems we rely on are all interconnected, and impacts and management choices within one sector may have cascading effects on the others (Ch. 17: Complex Systems, KM 1).

For example, wildfire trends in the western United States are influenced by rising temperatures and changing precipitation patterns, pest populations, and land management practices. As humans have moved closer to forestlands, increased fire suppression practices have reduced natural fires and led to denser vegetation, resulting in fires that are larger and more damaging when they do occur (Figures 1.5 and 1.2k) (Ch. 6: Forests, KM 1). Warmer winters have led to increased pest outbreaks and significant tree kills, with varying feedbacks on wildfire. Increased wildfire driven by climate change is projected to increase costs associated with health effects, loss of homes and other property, wildfire response, and fuel management. Failure to anticipate these interconnected impacts can lead to missed opportunities for effectively managing risks within a single sector and may actually increase risks to other sectors. Planning around wildfire risk and other risks affected by climate change entails the challenge of accounting for all of these influences and how they interact with one another (see Ch. 17: Complex Systems, Box 17.4).

Box 1.3: Interconnected Impacts of Climate Change, *continued*

New to this edition of the NCA, Chapter 17 (Complex Systems) highlights several examples of interconnected impacts and documents how a multisector perspective and joint management of systems can enhance resilience to a changing climate. It is often difficult or impossible to quantify and predict how all relevant processes and interactions in interconnected systems will respond to climate change. Non-climate influences, such as population changes, add to the challenges of projecting future outcomes (Ch. 17: Complex Systems, KM 2). Despite these challenges, there are opportunities to learn from experience to guide future risk management decisions. Valuable lessons can be learned retrospectively: after Superstorm Sandy in 2012, for example, the mayor of New York City initiated a Climate Change Adaptation Task Force that brought together stakeholders from several sectors such as water, transportation, energy, and communications to address the interdependencies among them (Ch. 17: Complex Systems, Box 17.1, KM 3).

Wildfire at the Wildland–Urban Interface

Figure 1.5: Wildfires are increasingly encroaching on American communities, posing threats to lives, critical infrastructure, and property. In October 2017, more than a dozen fires burned through northern California, killing dozens of people and leaving thousands more homeless. Communities distant from the fires were affected by poor air quality as smoke plumes darkened skies and caused the cancellation of school and other activities across the region. (left) A NASA satellite image shows active fires on October 9, 2017. (right) The Tubbs Fire, which burned parts of Napa, Sonoma, and Lake counties, was the most destructive in California's history. It caused an estimated $1.2 billion in damages and destroyed over 5,000 structures, including 5% of the housing stock in the city of Santa Rosa. *Image credits: (left) NASA; (right) Master Sgt. David Loeffler, U.S. Air National Guard.*

change beyond our borders are expected to increasingly affect our trade and economy, including import and export prices and U.S. businesses with overseas operation and supply chains (Box 1.4) (Ch. 16: International, KM 1; Ch. 17: Complex Systems, KM 1). Some aspects of our economy may see slight improvements in a modestly warmer world. However, the continued warming that is projected to occur without significant reductions in global greenhouse gas emissions is expected to cause substantial net damage to the U.S. economy, especially in the absence of increased adaptation efforts. The potential for losses in some sectors could reach hundreds of billions of dollars per year by the end of this century (Ch. 29: Mitigation, KM 2).

Existing water, transportation, and energy infrastructure already face challenges from heavy rainfall, inland and coastal flooding, landslides, drought, wildfire, heat waves, and other weather and climate events (Figures 1.5–1.9)

(Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1). Many extreme weather and climate-related events are expected to become more frequent and more intense in a warmer world, creating greater risks of infrastructure disruption and failure that can cascade across economic sectors (Ch. 3: Water, KM 2; Ch. 4: Energy, KM 1; Ch. 11: Urban, KM 3; Ch. 12: Transportation, KM 2). For example, more frequent and severe heat waves and other extreme events in many parts of the United States are expected to increase stresses on the energy system, amplifying the risk of more frequent and longer-lasting power outages and fuel shortages that could affect other critical sectors and systems, such as access to medical care (Ch. 17: Complex Systems, Box 17.5; Ch. 4: Energy, KM 1; Ch. 8: Coastal, KM 1; Ch. 11: Urban, KM 3; Ch. 12: Transportation, KM 3). Current infrastructure is typically designed for historical climate conditions (Ch. 12: Transportation, KM 1) and development patterns—for instance, coastal land use—generally do not account for a changing climate (Ch. 5: Land Changes, State of the Sector), resulting in increasing vulnerability to future risks from weather extremes and climate change (Ch. 11: Urban, KM 2). Infrastructure age and deterioration make failure or interrupted service from extreme weather even more likely (Ch. 11: Urban, KM 2). Climate change is expected to increase the costs of maintaining, repairing, and replacing infrastructure, with differences across regions (Ch. 12: Transportation, Regional Summary).

Recent extreme events demonstrate the vulnerabilities of interconnected economic sectors to increasing risks from climate change (see Box 1.3). In 2017, Hurricane Harvey dumped an unprecedented amount of rainfall over the greater Houston area, some of which has been attributed to human-induced climate change (Ch. 2: Climate, Box 2.5). Resulting power outages had cascading effects on critical infrastructure facilities such as hospitals and water and wastewater treatment plants. Reduced oil production and refining capacity in the Gulf of Mexico caused price spikes regionally and nationally from actual and anticipated gasoline shortages (Figure 1.6) (Ch. 17: Complex Systems, KM 1). In the U.S. Caribbean, Hurricanes Irma and Maria caused catastrophic damage to infrastructure, including the complete failure of Puerto Rico's power grid and the loss of power throughout the U.S. Virgin Islands, as well as extensive damage to the region's agricultural industry. The death toll in Puerto Rico grew in the three months following Maria's landfall on the island due in part to the lack of electricity and potable water as well as access to medical facilities and medical care (Ch. 20: U.S. Caribbean, Box 20.1, KM 5).

Climate-related risks to infrastructure, property, and the economy vary across regions. Along the U.S. coastline, public infrastructure and $1 trillion in national wealth held in coastal real estate are threatened by rising sea levels, higher storm surges, and the ongoing increase in high tide flooding (Figures 1.4 and 1.8) (Ch. 8: Coastal, KM 1). Coastal infrastructure provides critical lifelines to the rest of the country, including energy supplies and access to goods and services from overseas trade; increased damage to coastal facilities is expected to result in cascading costs and national impacts (Ch. 8: Coastal, KM 1; Ch. 4: Energy, State of the Sector, KM 1). High tide flooding is projected to become more disruptive and costlier as its frequency, depth, and inland extent grow in the coming decades. Without significant adaptation measures, many coastal cities in the Southeast are expected to experience daily high tide flooding by the end of the century (Ch. 8:

Widespread Impacts from Hurricane Harvey

Figure 1.6: Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. *From Figure 17.2, Ch. 17: Complex Systems (Photo credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard).*

Flooding at Fort Calhoun Nuclear Power Plant

Figure 1.7: Floodwaters from the Missouri River surround the Omaha Public Power District's Fort Calhoun Station, a nuclear power plant just north of Omaha, Nebraska, on June 20, 2011. The flooding was the result of runoff from near-record snowfall totals and record-setting rains in late May and early June. A protective berm holding back the floodwaters from the plant failed, which prompted plant operators to transfer offsite power to onsite emergency diesel generators. Cooling for the reactor temporarily shut down, but spent fuel pools were unaffected. *From Figure 22.5, Ch. 22: N. Great Plains (Photo credit: Harry Weddington, U.S. Army Corps of Engineers).*

Norfolk Naval Base at Risk from Rising Seas

Figure 1.8: Low-lying Norfolk, Virginia, houses the world's largest naval base, which supports multiple aircraft carrier groups and is the duty station for thousands of employees. Most of the area around the base lies less than 10 feet above sea level, and local relative sea level is projected to rise between about 2.5 and 11.5 feet by the year 2100 under the Lower and Upper Bound USGCRP sea level rise scenarios, respectively (see Scenario Products section of Appendix 3 for more details on these sea level rise scenarios; see also Ch. 8: Coastal, Case Study "Key Messages in Action—Norfolk, Virginia"). *Photo credit: Mass Communication Specialist 1st Class Christopher B. Stoltz, U.S. Navy.*

Coastal, KM 1; Ch. 19: Southeast, KM 2). Higher sea levels will also cause storm surge from tropical storms to travel farther inland than in the past, impacting more coastal properties and infrastructure (Ch. 8: Coastal: KM 1; Ch. 19: Southeast, KM 2). Oil, natural gas, and electrical infrastructure located along the coasts of the Atlantic Ocean and Gulf of Mexico are at increased risk of damage from rising sea levels and stronger hurricanes; regional disruptions are expected to have national implications (Ch. 4: Energy, State of the Sector, KM 1; Ch.

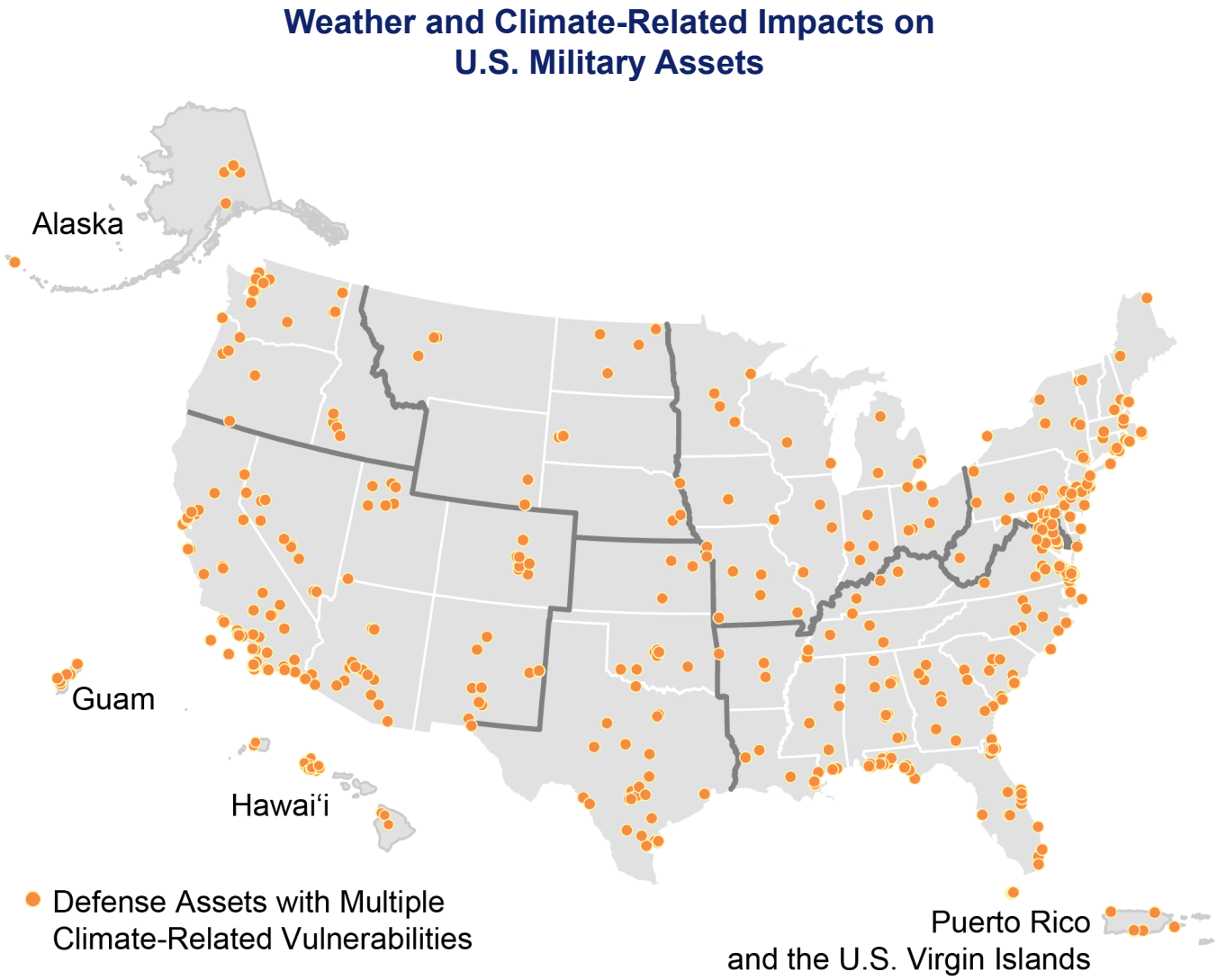


Figure 1.9: The Department of Defense (DoD) has significant experience in planning for and managing risk and uncertainty. The effects of climate and extreme weather represent additional risks to incorporate into the Department's various planning and risk management processes. To identify DoD installations with vulnerabilities to climate-related impacts, a preliminary Screening Level Vulnerability Assessment Survey (SLVAS) of DoD sites worldwide was conducted in 2015. The SLVAS responses (shown for the United States; orange dots) yielded a wide range of qualitative information. The highest number of reported effects resulted from drought (782), followed closely by wind (763) and non-storm surge related flooding (706). About 10% of sites indicated being affected by extreme temperatures (351), while flooding due to storm surge (225) and wildfire (210) affected about 6% of the sites reporting. The survey responses provide a preliminary qualitative picture of DoD assets currently affected by severe weather events as well as an indication of assets that may be affected by sea level rise in the future. *Source: adapted from Department of Defense 2018 (http://www.oea.gov/resource/2018-climate-related-risk-dod-infrastructure-initial-vulnerability-assessment-survey-slvas).*

18: Northeast, KM 3; Ch. 19: Southeast, KM 2). Hawai'i and the U.S.-Affiliated Pacific Islands and the U.S. Caribbean also face high risks to critical infrastructure from coastal flooding, erosion, and storm surge (Ch. 4: Energy, State of the Sector; Ch. 20: U.S. Caribbean, KM 3; Ch. 27: Hawai'i & Pacific Islands, KM 3).

In the western United States, increasing wildfire is damaging ranches and rangelands as well as property in cities near the wildland–urban interface. Drier conditions are projected to increase the risk of wildfires and damage to property and infrastructure, including energy production and generation assets and the power grid (Ch. 4: Energy, KM 1; Ch. 11: Urban, Regional Summary; Ch. 24: Northwest, KM 3). In Alaska, thawing of permafrost is responsible for severe damage to roads, buildings, and pipelines that will be costly to replace, especially in remote parts of Alaska. Alaska oil and gas operations are vulnerable to thawing permafrost, sea level rise, and increased coastal exposure due to declining sea ice; however, a longer ice-free season may enhance offshore energy operations and transport (Ch. 4: Energy, State of the Sector; Ch. 26: Alaska, KM 2 and 5). These impacts are expected to grow with continued warming.

U.S. agriculture and the communities it supports are threatened by increases in temperatures, drought, heavy precipitation events, and wildfire on rangelands (Figure 1.10) (Ch. 10: Ag & Rural, KM 1 and 2, Case Study "Groundwater Depletion in the Ogallala Aquifer Region"; Ch. 23: S. Great Plains, KM 1, Case Study "The Edwards Aquifer"). Yields of major U.S. crops (such as corn, soybeans, wheat, rice, sorghum, and cotton) are expected to decline over this century as a consequence of increases in temperatures and possibly changes in water availability and disease and pest outbreaks (Ch. 10: Ag & Rural, KM 1). Increases in growing season temperatures in the Midwest are projected to be the largest contributing factor to declines in U.S. agricultural productivity (Ch. 21: Midwest, KM 1). Climate change is also expected to lead to large-scale shifts in the availability and prices of many agricultural products across the world, with corresponding impacts on U.S. agricultural producers and the U.S. economy (Ch. 16: International, KM 1).

Conservation Practices Reduce Impact of Heavy Rains

Figure 1.10: Increasing heavy rains are leading to more soil erosion and nutrient loss on midwestern cropland. Integrating strips of native prairie vegetation into row crops has been shown to reduce soil and nutrient loss while improving biodiversity. The inset shows a close-up example of a prairie vegetation strip. *From Figure 21.2, Ch. 21: Midwest (Photo credits: [main photo] Lynn Betts; [inset] Farnaz Kordbacheh).*

Extreme heat poses a significant risk to human health and labor productivity in the agricultural, construction, and other outdoor sectors (Ch. 10: Ag & Rural, KM 3). Under a higher scenario (RCP8.5), almost two billion labor hours are projected to be lost annually by 2090 from the impacts of temperature extremes, costing an estimated $160 billion in lost wages (Ch. 14: Human Health, KM 4). States within the Southeast (Ch. 19: Southeast, KM 4) and Southern Great Plains (Ch. 23: S. Great Plains, KM 4)

regions are projected to experience some of the greatest impacts (see Figure 1.21).

Natural Environment and Ecosystem Services

Climate change threatens many benefits that the natural environment provides to society: safe and reliable water supplies, clean air, protection from flooding and erosion, and the use of natural resources for economic, recreational, and subsistence activities. Valued aspects of regional heritage and quality of life tied to the natural environment, wildlife, and outdoor recreation will change with the climate, and as a result, future generations can expect to experience and interact with natural systems in ways that are much different than today. Without significant reductions in greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided, with varying impacts on the economic, recreational, and subsistence activities they support.

Changes affecting the quality, quantity, and availability of water resources, driven in part by climate change, impact people and the environment (Ch. 3: Water, KM 1). Dependable and safe water supplies for U.S. Caribbean, Hawai'i, and U.S.-Affiliated Pacific Island communities and ecosystems are threatened by rising temperatures, sea level rise, saltwater intrusion, and increased risks of drought and flooding (Ch. 3: Water, Regional Summary; Ch. 20: U.S. Caribbean, KM 1; Ch. 27: Hawai'i & Pacific Islands, KM 1). In the Midwest, the occurrence of conditions that contribute to harmful algal blooms, which can result in restrictions to water usage for drinking and recreation, is expected to increase (Ch. 3: Water, Regional Summary; Ch. 21: Midwest, KM 3). In the Southwest, water supplies for people and nature are decreasing during droughts due in part to climate change. Intensifying droughts, heavier downpours, and reduced snowpack are combining with other stressors such as groundwater depletion to reduce the future reliability of water supplies in the region, with cascading impacts on energy production and other water-dependent sectors (Ch. 3: Water, Regional Summary; Ch. 4: Energy, State of the Sector; Ch. 25: Southwest, KM 5). In the Southern Great Plains, current drought and projected increases in drought length and severity threaten the availability of water for agriculture (Figures 1.11 and 1.12) (Ch. 23: S. Great Plains, KM 1). Reductions in mountain snowpack and shifts in snowmelt timing are expected to reduce hydropower production in the Southwest and the Northwest (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). Drought is expected to threaten oil and gas drilling and refining as well as thermoelectric power plants that rely on a steady supply of water for cooling (Ch. 4: Energy, State of the Sector, KM 1; Ch. 22: N. Great Plains, KM 4; Ch. 23: S. Great Plains, KM 2; Ch. 25: Southwest, KM 5).

Impacts of Drought on Texas Agriculture

Figure 1.11: Soybeans in Texas experience the effects of drought in August 2013. During 2010–2015, a multiyear regional drought severely affected agriculture in the Southern Great Plains. One prominent impact was the reduction of irrigation water released for farmers on the Texas coastal plains. *Photo credit: Bob Nichols, USDA*.

Desalination Plants Can Reduce Impacts from Drought in Texas

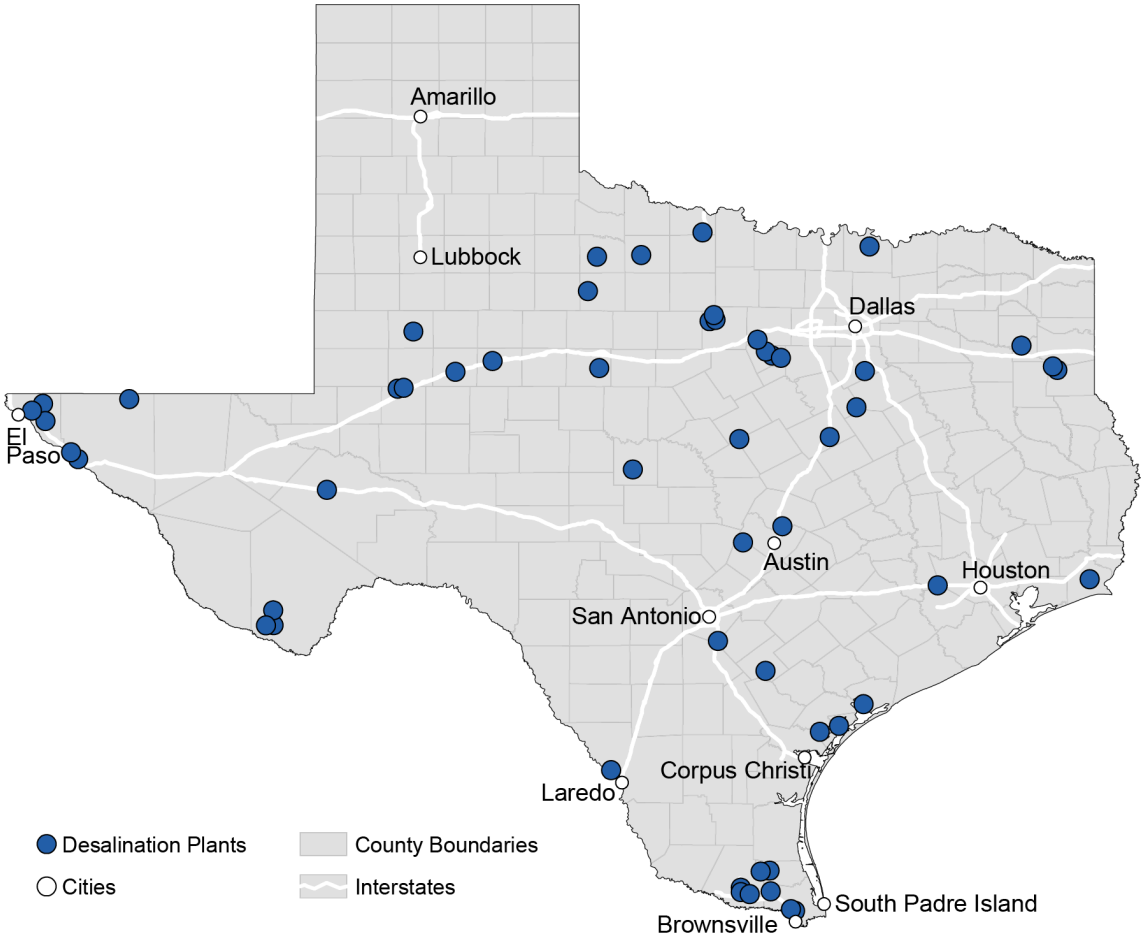


Figure 1.12: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. The state's 2017 Water Plan recommended an expansion of desalination to help reduce longer-term risks to water supplies from drought, higher temperatures, and other stressors. There are currently 44 public water supply desalination plants in Texas. *From Figure 23.8, Ch. 23: S. Great Plains (Source: adapted from Texas Water Development Board 2017)*.

Tourism, outdoor recreation, and subsistence activities are threatened by reduced snowpack, increases in wildfire activity, and other stressors affecting ecosystems and natural resources (Figures 1.2d, 1.2k, and 1.13) (Ch. 7: Ecosystems, KM 3). Increasing wildfire frequency (Ch. 19: Southeast, Case Study "Prescribed Fire"), pest and disease outbreaks (Ch. 21: Midwest, Case Study "Adaptation in Forestry"), and other stressors are projected to reduce the ability of U.S. forests to support recreation as well as economic and subsistence activities (Ch. 6: Forests, KM 1 and 2; Ch. 19: Southeast, KM 3; Ch. 21: Midwest, KM 2). Increases in wildfire smoke events driven by climate change are expected to reduce the amount and quality of time spent in outdoor activities (Ch. 13: Air Quality, KM 2; Ch. 24: Northwest, KM 4). Projected declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States are expected to adversely impact the winter recreation industry (Ch. 18: Northeast, KM 1; Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 1, Box 24.7). In the Northeast, activities that rely on natural snow and ice cover may not be economically viable by the

Razor Clamming on the Washington Coast

Figure 1.13: Razor clamming draws crowds on the coast of Washington State. This popular recreation activity is expected to decline due to ocean acidification, harmful algal blooms, warmer temperatures, and habitat degradation. *From Figure 24.7, Ch. 24: Northwest (Photo courtesy of Vera Trainer, NOAA).*

end of the century without significant reductions in global greenhouse gas emissions (Ch. 18: Northeast, KM 1). Diminished snowpack, increased wildfire, pervasive drought, flooding, ocean acidification, and sea level rise directly threaten the viability of agriculture, fisheries, and forestry enterprises on tribal lands across the United States and impact tribal tourism and recreation sectors (Ch. 15: Tribes, KM 1).

Climate change has already had observable impacts on biodiversity and ecosystems throughout the United States that are expected to continue. Many species are shifting their ranges (Figure 1.2h), and changes in the timing of important biological events (such as migration and reproduction) are occurring in response to climate change (Ch. 7: Ecosystems, KM 1). Climate change is also aiding the spread of invasive species (Ch. 21: Midwest, Case Study "Adaptation in Forestry"; Ch. 22: N. Great Plains, Case Study "Crow Nation and the Spread of Invasive Species"), recognized as a major driver of biodiversity loss and substantial ecological and economic costs globally (Ch. 7: Ecosystems, Invasive Species). As environmental conditions change further, mismatches between species and the availability of the resources they need to survive are expected to occur (Ch. 7: Ecosystems, KM 2). Without significant reductions in global greenhouse gas emissions, extinctions and transformative impacts on some ecosystems cannot be avoided in the long term (Ch. 9: Oceans, KM 1). While some new opportunities may emerge from ecosystem changes, economic and recreational opportunities and cultural heritage based around historical use of species or natural resources in many areas are at risk (Ch. 7: Ecosystems, KM 3; Ch. 18: Northeast, KM 1 and 2, Box 18.6).

Ocean warming and acidification pose high and growing risks for many marine organisms, and the impacts of climate change on ocean ecosystems are expected to lead to reductions in important ecosystem services such as aquaculture, fishery productivity, and recreational opportunities (Ch 9: Oceans, KM 2). While climate change impacts on ocean ecosystems are widespread, the scope of ecosystem impacts occurring in tropical and polar areas is greater than anywhere else in the world. Ocean warming is already leading to reductions in vulnerable coral reef and sea ice habitats that support the livelihoods of many communities (Ch. 9: Oceans, KM 1). Decreasing sea ice extent in the Arctic represents a direct loss of important habitat for marine mammals, causing declines in their populations (Figure 1.2f) (Ch. 26: Alaska, Box 26.1). Changes in spring ice melt have affected the ability of coastal communities in Alaska to meet their walrus harvest needs in recent years (Ch. 26: Alaska, KM 1). These changes are expected to continue as sea ice declines further (Ch. 2: Climate, KM 7). In the tropics, ocean warming has already led to widespread coral reef bleaching and/or outbreaks of coral diseases off the coastlines of Puerto

Severe Coral Bleaching Projected for Hawai‘i and the U.S.-Affiliated Pacific Islands

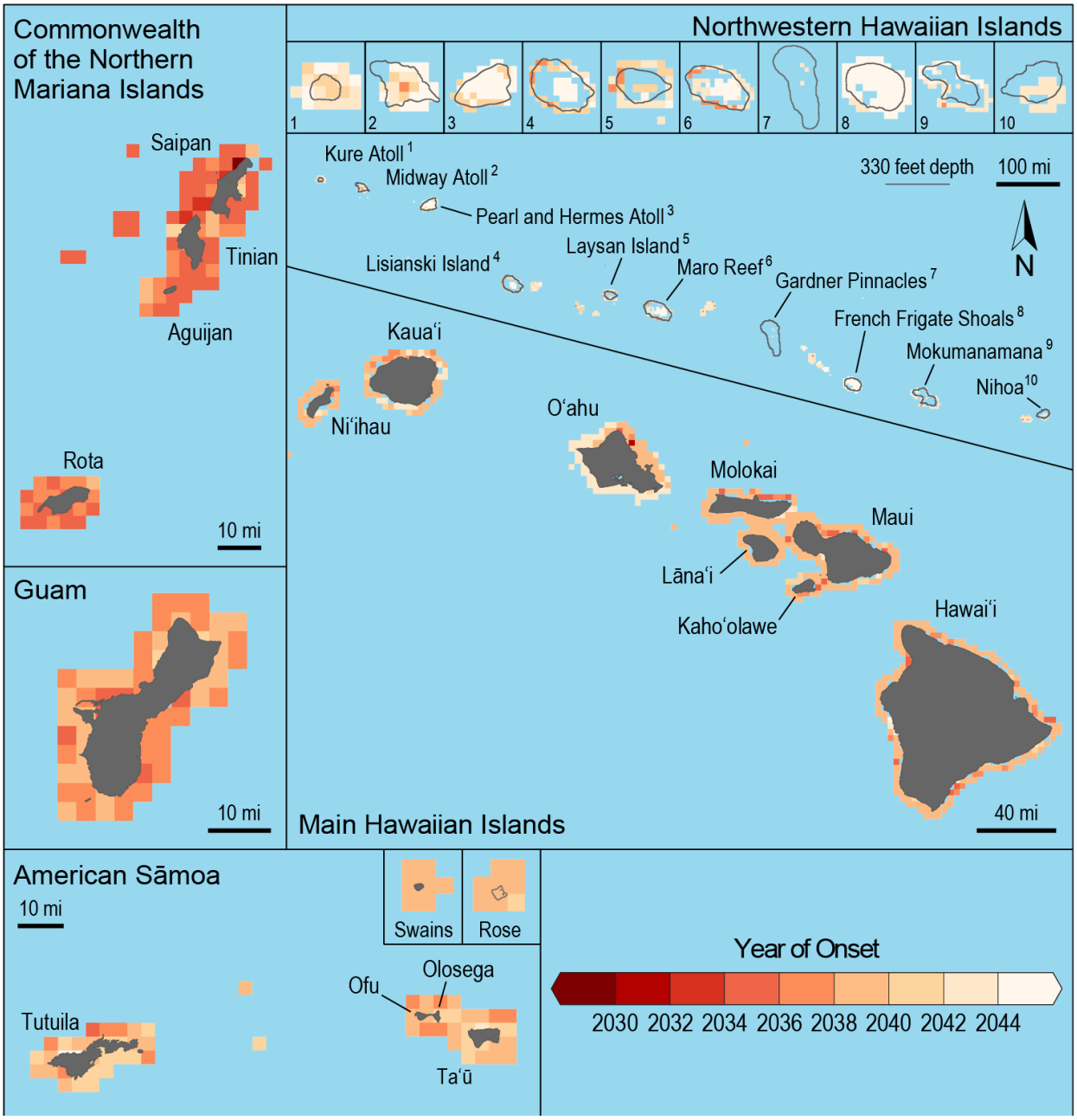


Figure 1.14: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. *From Figure 27.10, Ch. 27: Hawai‘i & Pacific Islands (Source: NOAA).*

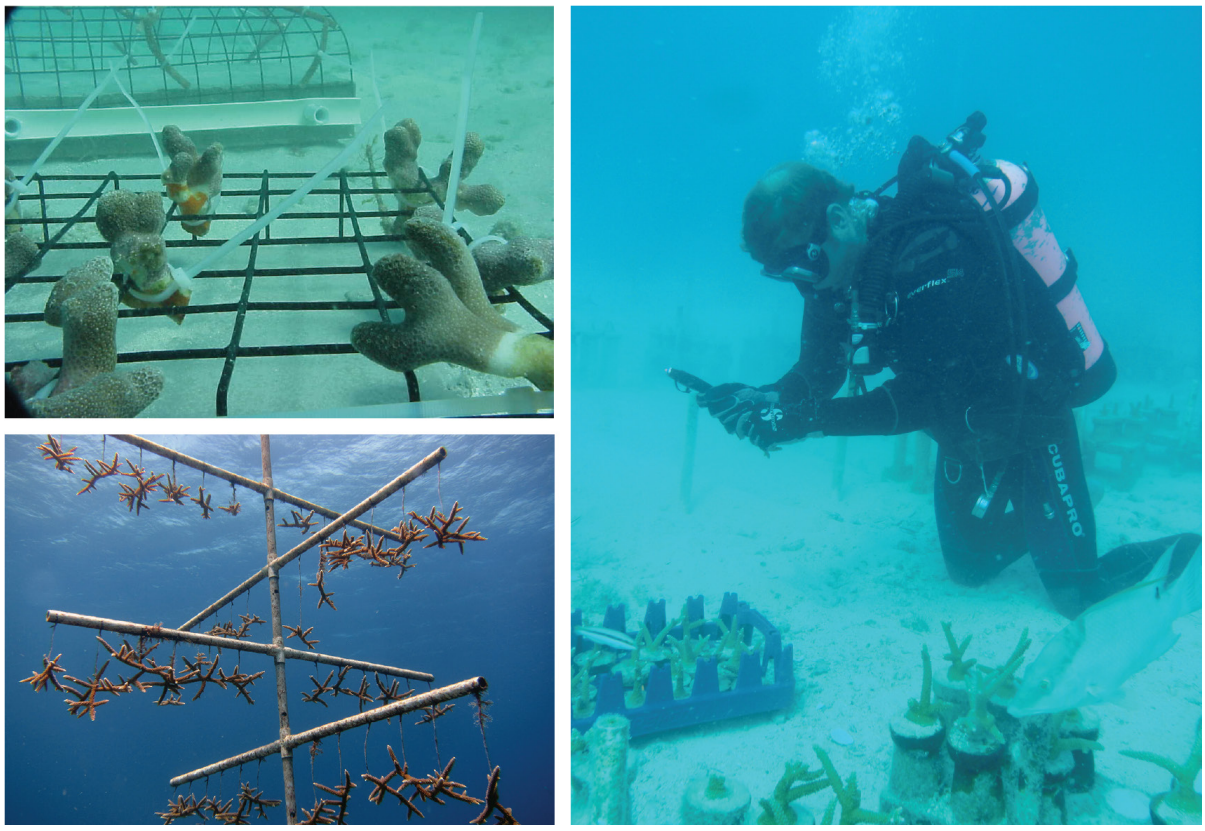
Rico, the U.S. Virgin Islands, Florida, and Hawai‘i and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4). By mid-century, widespread coral bleaching is projected to occur annually in Hawai‘i and the U.S.-Affiliated Pacific Islands (Figure 1.14). Bleaching and ocean acidification are expected to result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat, with impacts on

tourism and livelihoods in both regions (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 4). While some targeted response actions are underway (Figure 1.15), many impacts, including losses of unique coral reef and sea ice ecosystems, can only be avoided by significantly reducing global greenhouse gas emissions, particularly carbon dioxide (Ch. 9: Oceans, KM 1).

Human Health and Well-Being

Higher temperatures, increasing air quality risks, more frequent and intense extreme weather and climate-related events, increases in coastal flooding, disruption of ecosystem services, and other changes increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable. Future climate change is expected to further disrupt many areas of life, exacerbating existing challenges and revealing new risks to health and prosperity.

Rising temperatures pose a number of threats to human health and quality of life (Figure 1.16). High temperatures in the summer are linked directly to an increased risk of illness and death, particularly among older adults, pregnant women, and children (Ch. 18: Northeast, Box 18.3). With continued warming,



Promoting Coral Reef Recovery

Figure 1.15: Examples of coral farming in the U.S. Caribbean and Florida demonstrate different types of structures used for growing fragments from branching corals. Coral farming is a strategy meant to improve the reef community and ecosystem function, including for fish species. The U.S. Caribbean Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands face similar threats from coral bleaching and mortality due to warming ocean surface waters and ocean acidification. Degradation of coral reefs is expected to negatively affect fisheries and the economies that depend on them as habitat is lost in both regions. While coral farming may provide some targeted recovery, current knowledge and efforts are not nearly advanced enough to compensate for projected losses from bleaching and acidification. *From Figure 20.11, Ch. 20: U.S. Caribbean (Photo credits: [top left] Carlos Pacheco, U.S. Fish and Wildlife Service; [bottom left] NOAA; [right] Florida Fish and Wildlife).*

Projected Change in Very Hot Days by 2100 in Phoenix, Arizona

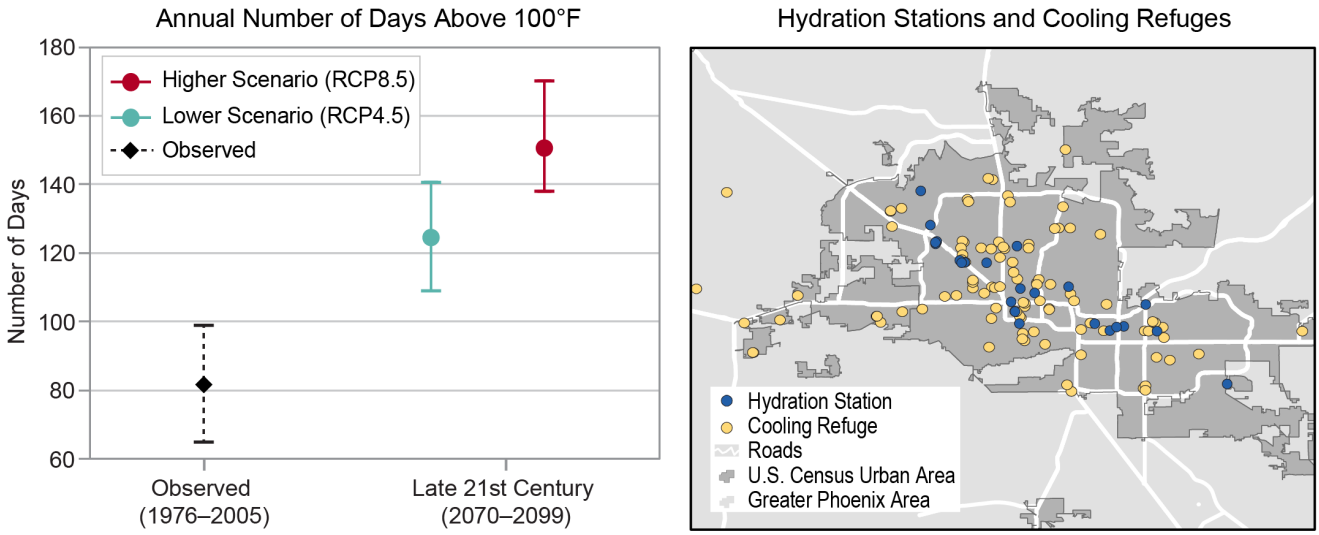


Figure 1.16: (left) The chart shows the average annual number of days above 100°F in Phoenix, Arizona, for 1976–2005, and projections of the average number of days per year above 100°F through the end of the 21st century (2070–2099) under the lower (RCP4.5) and higher (RCP8.5) scenarios. Dashed lines represent the 5th–95th percentile range of annual observed values. Solid lines represent the 5th–95th percentile range of projected model values. (right) The map shows hydration stations and cooling refuges (cooled indoor locations that provide water and refuge from the heat during the day) in Phoenix in August 2017. Such response measures for high heat events are expected to be needed at greater scales in the coming years if the adverse health effects of more frequent and severe heat waves are to be minimized. *Sources: (left) NOAA NCEI, CICS-NC, and LMI; (right) adapted from Southwest Cities Heat Refuges (a project by Arizona State University's Resilient Infrastructure Lab), available at http://www.coolme.today/#phoenix. Data provided by Andrew Fraser and Mikhail Chester, Arizona State University.*

cold-related deaths are projected to decrease and heat-related deaths are projected to increase. In most regions, the increases in heat-related deaths are expected to outpace the reductions in cold-related deaths (Ch. 14: Human Health, KM 1). Rising temperatures are expected to reduce electricity generation capacity while increasing energy demands and costs, which can in turn lead to power outages and blackouts (Ch. 4: Energy, KM 1; Ch. 11: Urban, Regional Summary, Figure 11.2). These changes strain household budgets, increase people's exposure to heat, and limit delivery of medical and social services. Risks from heat stress are higher for people without access to housing with sufficient insulation or air conditioning (Ch. 11: Urban, KM 1).

Changes in temperature and precipitation can increase air quality risks from wildfire and ground-level ozone (smog). Projected increases in wildfire activity due to climate change would further degrade air quality, resulting in increased health risks and impacts on quality of life (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1). Unless counteracting efforts to improve air quality are implemented, climate change is expected to worsen ozone pollution across much of the country, with adverse impacts on human health (Figure 1.21) (Ch. 13: Air Quality, KM 1). Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can also increase exposure to airborne pollen allergens. The frequency and severity of allergic illnesses, including asthma and hay fever, are expected to increase as a result of a changing climate (Ch. 13: Air Quality, KM 3).

Rising air and water temperatures and changes in extreme weather and climate-related events are expected to increase exposure to

waterborne and foodborne diseases, affecting food and water safety. The geographic range and distribution of disease-carrying insects and pests are projected to shift as climate changes, which could expose more people in North America to ticks that carry Lyme disease and mosquitoes that transmit viruses such as West Nile, chikungunya, dengue, and Zika (Ch. 14: Human Health, KM 1; Ch. 16: International, KM 4).

Mental health consequences can result from exposure to climate- or extreme weather-related events, some of which are projected to intensify as warming continues (Ch. 14: Human Health, KM 1). Coastal city flooding as a result of sea level rise and hurricanes, for example, can result in forced evacuation, with adverse effects on family and community stability as well as mental and physical health (Ch. 11: Urban, KM 1). In urban areas, disruptions in food supply or safety related to extreme weather or climate-related events are expected to disproportionately impact those who already experience food insecurity (Ch. 11: Urban, KM 3).

Indigenous peoples have historical and cultural relationships with ancestral lands, ecosystems, and culturally important species that are threatened by climate change (Ch. 15: Tribes, KM 1; Ch. 19: Southeast, KM 4, Case Study "Mountain Ramps"; Ch. 24: Northwest, KM 5). Climate change is expected to compound existing physical health issues in Indigenous communities, in part due to the loss of traditional foods and practices, and in some cases, the mental stress from permanent community displacement (Ch. 14: Human Health, KM 2; Ch. 15: Tribes, KM 2). Throughout the United States, Indigenous peoples are considering or actively pursuing relocation as an adaptation strategy in response to climate-related disasters, more frequent flooding, loss of land due to erosion, or as livelihoods are compromised by ecosystem shifts linked to climate change (Ch. 15: Tribes, KM 3). In Louisiana, a federal grant is being used to relocate the tribal community of Isle de Jean Charles in response to severe land loss, sea level rise, and coastal flooding (Figure 1.17) (Ch. 19: Southeast, KM 2, Case Study "A Lesson Learned for Community Resettlement"). In Alaska, coastal Native communities are already

Community Relocation—Isle de Jean Charles, Louisiana

Figure 1.17: (left) A federal grant is being used to relocate the tribal community of Isle de Jean Charles, Louisiana, in response to severe land loss, sea level rise, and coastal flooding. *From Figure 15.3, Ch. 15: Tribes (Photo credit: Ronald Stine)*. (right) As part of the resettlement of the tribal community of Isle de Jean Charles, residents are working with the Lowlander Center and the State of Louisiana to finalize a plan that reflects the desires of the community. *From Figure 15.4, Ch. 15: Tribes (Photo provided by Louisiana Office of Community Development)*.

Adaptation Measures in Kivalina, Alaska

Figure 1.18: A rock revetment was installed in the Alaska Native Village of Kivalina in 2010 to reduce increasing risks from erosion. A new rock revetment wall has a projected lifespan of 15 to 20 years. *From Figure 15.3, Ch. 15: Tribes (Photo credit: ShoreZone. Creative Commons License CC BY 3.0: https://creativecommons.org/licenses/by/3.0/legalcode)*. The inset shows a close-up of the rock wall in 2011. *Photo credit: U.S. Army Corps of Engineers–Alaska District.*

experiencing heightened erosion driven by declining sea ice, rising sea levels, and warmer waters (Figure 1.18). Coastal and river erosion and flooding in some cases will require parts of communities, or even entire communities, to relocate to safer terrain (Ch. 26: Alaska, KM 2). Combined with other stressors, sea level rise, coastal storms, and the deterioration of coral reef and mangrove ecosystems put the long-term habitability of coral atolls in the Hawai'i and U.S.-Affiliated Pacific Islands region at risk, introducing issues of sovereignty, human and national security, and equity (Ch. 27: Hawai'i & Pacific Islands, KM 6).

Reducing the Risks of Climate Change

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high greenhouse gas emissions and limited or no adaptation. Recent findings reinforce the fact that without substantial and sustained reductions in greenhouse gas emissions and regional adaptation efforts, there will be substantial and far-reaching changes over the course of the 21st century with negative consequences for a large majority of sectors, particularly towards the end of the century.

The impacts and costs of climate change are already being felt in the United States, and changes in the likelihood or severity of some recent extreme weather events can now be attributed with increasingly higher confidence to human-caused warming (see CSSR, Ch. 3). Impacts associated with human health, such as premature deaths due to extreme temperatures and poor air quality, are some of the most

Box 1.4: How Climate Change Around the World Affects the United States

The impacts of changing weather and climate patterns beyond U.S. international borders affect those living in the United States, often in complex ways that can generate both challenges and opportunities. The International chapter (Ch. 16), new to this edition of the NCA, assesses our current understanding of how global climate change, natural variability, and associated extremes are expected to impact—and in some cases are already impacting—U.S. interests both within and outside of our borders.

Current and projected climate-related impacts on our economy include increased risks to overseas operations of U.S. businesses, disruption of international supply chains, and shifts in the availability and prices of commodities. For example, severe flooding in Thailand in 2011 disrupted the supply chains for U.S. electronics manufacturers (Ch. 16: International, Figure 16.1). U.S. firms are increasingly responding to climate-related risks, including through their financial disclosures and partnerships with environmental groups (Ch. 16: International, KM 1).

Impacts from climate-related events can also undermine U.S. investments in international development by slowing or reversing social and economic progress in developing countries, weakening foreign markets for U.S. exports, and increasing the need for humanitarian assistance and disaster relief efforts. Predictive tools can help vulnerable countries anticipate natural disasters, such as drought, and manage their impacts. For example, the United States and international partners created the Famine Early Warning Systems Network (FEWS NET), which helped avoid severe food shortages in Ethiopia during a historic drought in 2015 (Ch. 16: International, KM 2).

Natural variability and changes in climate increase risks to our national security by affecting factors that can exacerbate conflict and displacement outside of U.S. borders, such as food and water insecurity and commodity price shocks. More directly, our national security is impacted by damage to U.S. military assets such as roads, runways, and waterfront infrastructure from extreme weather and climate-related events (Figures 1.8 and 1.9). The U.S. military is working to both fully understand these threats and incorporate projected climate changes into long-term planning. For example, the Department of Defense has performed a comprehensive scenario-driven examination of climate risks from sea level rise to all of its coastal military sites, including atolls in the Pacific Ocean (Ch. 16: International, KM 3).

Finally, the impacts of climate change are already affecting the ecosystems that span our Nation's borders and the communities that rely on them. International frameworks for the management of our shared resources continue to be restructured to incorporate risks from these impacts. For example, a joint commission that implements water treaties between the United States and Mexico is exploring adaptive water management strategies that account for the effects of climate change and natural variability on Colorado River water (Ch. 16: International, KM 4).

substantial (Ch. 13: Air Quality, KM 1; Ch. 14: Human Health, KM 1 and 4; Ch 29: Mitigation, KM 2). While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources. Further, some impacts will very likely be irreversible for thousands of years, including those to species, such as corals (Ch. 9: Oceans, KM 1; Ch. 27: Hawai'i & Pacific Islands, KM 4), or that involve the crossing of thresholds, such as the effects of ice sheet disintegration on accelerated sea level

rise, leading to widespread effects on coastal development lasting thousands of years (Ch. 29: Mitigation, KM 2).

Future impacts and risks from climate change are directly tied to decisions made in the present, both in terms of mitigation to reduce emissions of greenhouse gases (or remove carbon dioxide from the atmosphere) and adaptation to reduce risks from today's changed climate conditions and prepare for future impacts. Mitigation and adaptation activities can be considered complementary strategies—mitigation efforts can reduce future risks, while adaptation actions can minimize the consequences of changes that are already happening as a result of past and present greenhouse gas emissions.

Many climate change impacts and economic damages in the United States can be substantially reduced through global-scale reductions in greenhouse gas emissions complemented by regional and local adaptation efforts (Ch 29: Mitigation, KM 4). Our understanding of the magnitude and timing of risks that can be avoided varies by sector, region, and assumptions about how adaptation measures change the exposure and vulnerability of people, livelihoods, ecosystems, and infrastructure. Acting sooner rather than later generally results in lower costs overall for both adaptation and mitigation efforts and can offer other benefits in the near term (Ch. 29: Mitigation, KM 3).

Since the Third National Climate Assessment (NCA3) in 2014, a growing number of states, cities, and businesses have pursued or expanded upon initiatives aimed at reducing greenhouse gas emissions, and the scale of adaptation implementation across the country has increased. However, these efforts do not yet approach the scale needed to avoid substantial damages to the economy, environment, and human health expected over the coming decades (Ch. 28: Adaptation, KM 1; Ch. 29: Mitigation, KM 1 and 2).

Mitigation

Many activities within the public and private sectors aim for or have the effect of reducing greenhouse gas emissions, such as the increasing use of natural gas in place of coal or the expansion of wind and solar energy to generate electricity. Fossil fuel combustion accounts for approximately 85% of total U.S. greenhouse gas emissions, with agriculture, land-cover change, industrial processes, and methane from fossil fuel extraction and processing as well as from waste (including landfills, wastewater treatment, and composting) accounting for most of the remainder. A number of efforts exist at the federal level to promote low-carbon energy technologies and to increase soil and forest carbon storage.

State, local, and tribal government approaches to mitigating greenhouse gas emissions include comprehensive emissions reduction strategies as well as sector- and technology-specific policies (see Figure 1.19). Since NCA3, private companies have increasingly reported their greenhouse gas emissions, announced emissions reductions targets, implemented actions to achieve those targets, and, in some cases, even put an internal price on carbon. Individuals and other organizations are also making choices every day to reduce their carbon footprints.

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. greenhouse gas emissions over the past decade. In 2016, U.S.

Mitigation-Related Activities at State and Local Levels

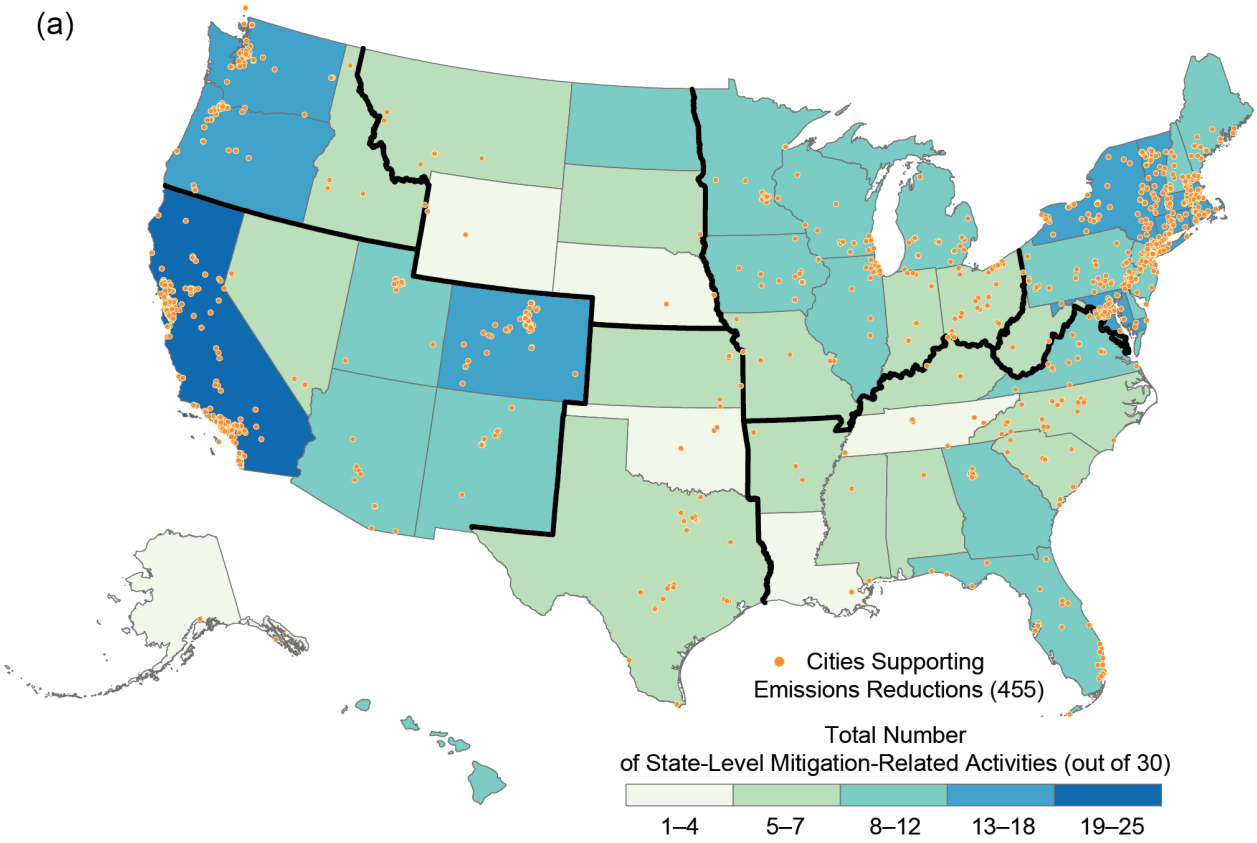


Figure 1.19: (a) The map shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; (b) the chart depicts the type and number of activities by state. Several territories also have a variety of mitigation-related activities, including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. *From Figure 29.1, Ch. 29: Mitigation (Sources: [a] EPA and ERT, Inc. [b] adapted from America's Pledge 2017).*

emissions were at their lowest levels since 1994. Power sector emissions were 25% below 2005 levels in 2016, the largest emissions reduction for a sector of the American economy over this time. This decline was in large part due to increases in natural gas and renewable energy generation, as well as enhanced energy efficiency standards and programs (Ch. 4: Energy, KM 2). Given these advances in electricity generation, transmission, and distribution, the largest annual sectoral emissions in the United States now come from transportation. As of the writing of this report, business-as-usual (as in, no new policies) projections of U.S. carbon dioxide and other greenhouse gas emissions show flat or declining trajectories over the next decade with a central estimate of about 15% to 20% reduction below 2005 levels by 2025 (Ch. 29: Mitigation, KM 1).

Recent studies suggest that some of the indirect effects of mitigation actions could significantly reduce—or possibly even completely offset—the potential costs associated with cutting greenhouse gas emissions. Beyond reduction of climate pollutants, there are many benefits, often immediate, associated with greenhouse gas emissions reductions, such as improving air quality and public health, reducing crop damages from ozone, and increasing energy independence and security through increased reliance on domestic sources of energy (Ch. 13: Air Quality, KM 4; Ch. 29: Mitigation, KM 4).

Adaptation

Many types of adaptation actions exist, including changes to business operations, hardening infrastructure against extreme weather, and adjustments to natural resource management strategies. Achieving the benefits of adaptation can require upfront investments to achieve longer-term savings, engaging with different stakeholder interests and values, and planning under uncertainty. In many sectors, adaptation can reduce the cost of climate impacts by more than half (Ch. 28: Adaptation, KM 4; Ch. 29: Mitigation, KM 4).

At the time of NCA3's release in 2014, its authors found that risk assessment and planning were underway throughout the United States but that on-the-ground implementation was limited. Since then, the scale and scope of adaptation implementation has increased, including by federal, state, tribal, and local agencies as well as business, academic, and nonprofit organizations (Figure 1.20). While the level of implementation is now higher, it is not yet common nor uniform across the United States, and the scale of implementation for some effects and locations is often considered inadequate to deal with the projected scale of climate change risks. Communities have generally focused on actions that address risks from current climate variability and recent extreme events, such as making buildings and other assets incrementally less sensitive to climate impacts. Fewer communities have focused on actions to address the anticipated scale of future change and emergent threats, such as reducing exposure by preventing building in high-risk locations or retreating from at-risk coastal areas (Ch. 28: Adaptation, KM 1).

Many adaptation initiatives can generate economic and social benefits in excess of their costs in both the near and long term (Ch. 28: Adaptation, KM 4). Damages to infrastructure, such as road and rail networks, are particularly sensitive to adaptation assumptions, with proactive measures that account for future climate risks estimated to be capable of reducing damages by large fractions. More than half of damages to coastal property are estimated to

Figure 1.20: Adaptation entails a continuing risk management process. With this approach, individuals and organizations become aware of and assess risks and vulnerabilities from climate and other drivers of change, take actions to reduce those risks, and learn over time. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014; darker color indicates more activity. *From Figure 28.1, Ch. 28: Adaptation (Source: adapted from National Research Council, 2010. Used with permission from the National Academies Press, © 2010, National Academy of Sciences. Image credits, clockwise from top: National Weather Service; USGS; Armando Rodriguez, Miami-Dade County; Dr. Neil Berg, MARISA; Bill Ingalls, NASA).*

be avoidable through adaptation measures such as shoreline protection and beach replenishment (Ch. 29: Mitigation, KM 4). Considerable guidance is available on actions whose benefits exceed their costs in some sectors (such as adaptation responses to storms and rising seas in coastal zones, to riverine and extreme precipitation flooding, and for agriculture at the farm level), but less so on other actions (such as those aimed at addressing risks to health, biodiversity, and ecosystems services) that may provide significant benefits but are not as well understood (Ch. 28: Adaptation, KM 4).

Effective adaptation can also enhance social welfare in many ways that can be difficult to quantify, including improving economic opportunity, health, equity, national security, education, social connectivity, and sense of place, while safeguarding cultural resources and enhancing environmental quality. Aggregating these benefits into a single monetary

value is not always the best approach, and more fundamentally, communities may value benefits differently. Considering various outcomes separately in risk management processes can facilitate participatory planning processes and allow for a specific focus on equity. Prioritizing adaptation actions for populations that face higher risks from climate change, including low-income and marginalized communities, may prove more equitable and lead, for instance, to improved infrastructure in their communities and increased focus on efforts to promote community resilience that can improve their capacity to prepare for, respond to, and recover from disasters (Ch. 28: Adaptation, KM 4).

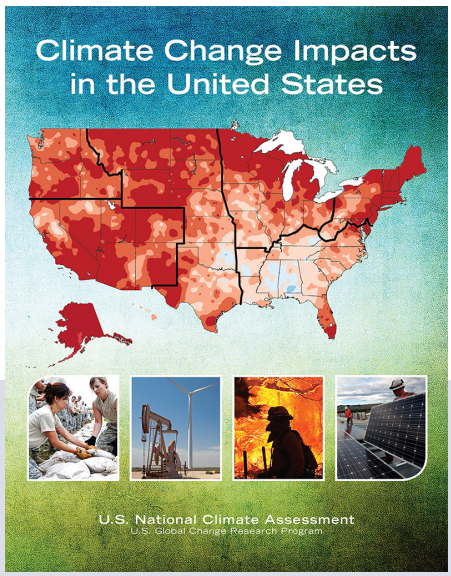
A significant portion of climate risk can be addressed by integrating climate adaptation into existing investments, policies, and practices. Integration of climate adaptation into decision processes has begun in many areas including financial risk reporting, capital investment planning, engineering standards, military planning, and disaster risk management. A growing number of jurisdictions address climate risk in their land-use, hazard mitigation, capital improvement, and transportation plans, and a small number of cities explicitly link their coastal and hazard mitigation plans using analysis of future climate risks. However, over the course of this century and especially under a higher scenario (RCP8.5), reducing the risks of climate change may require more significant changes to policy and regulations at all scales, community planning, economic and financial systems, technology applications, and ecosystems (Ch. 28: Adaptation, KM 5).

Some sectors are already taking actions that go beyond integrating climate risk into current practices. Faced with substantial climate-induced changes in the future, including new invasive species and shifting ranges for native species, ecosystem managers have already begun to adopt new approaches such as assisted migration and development of wildlife corridors (Ch. 7: Ecosystems, KM 2). Many millions of Americans live in coastal areas threatened by sea level rise; in all but the very lowest sea level rise projections, retreat will become an unavoidable option in some areas along the U.S. coastline (Ch. 8: Coastal, KM 1). The Federal Government has granted funds for the relocation of some communities, including the Biloxi-Chitimacha-Choctaw Tribe from Isle de Jean Charles in Louisiana (Figure 1.17). However, the potential need for millions of people and billions of dollars of coastal infrastructure to be relocated in the future creates challenging legal, financial, and equity issues that have not yet been addressed (Ch. 28: Adaptation, KM 5).

In some areas, lack of historical or current data to inform policy decisions can be a limitation to assessments of vulnerabilities and/or effective adaptation planning. For this National Climate Assessment, this was particularly the case for some aspects of the Alaska, U.S. Caribbean, and Hawai'i and U.S.-Affiliated Pacific Islands regions. In many instances, relying on Indigenous knowledges is among the only current means of reconstructing what has happened in the past. To help communities across the United States learn from one another in their efforts to build resilience to a changing climate, this report highlights common climate-related risks and possible response actions across all regions and sectors.

What Has Happened Since the Last National Climate Assessment?

Our understanding of and experience with climate science, impacts, risks, and adaptation in the United States have grown significantly since the Third National Climate Assessment (NCA3), advancing our knowledge of key processes in the earth system, how human and natural forces are changing them, what the implications are for society, and how we can respond.



Key Scientific Advances

Detection and Attribution: Significant advances have been made in the attribution of the human influence for individual climate and weather extreme events (see CSSR, Chs. 3, 6, 7, and 8).

Extreme Events and Atmospheric Circulation: How climate change may affect specific types of extreme events in the United States and the extent to which atmospheric circulation in the midlatitudes is changing or is projected to change, possibly in ways not captured by current climate models, are important areas of research where scientific understanding has advanced (see CSSR, Chs. 5, 6, 7, and 9).

Localized Information: As computing resources have grown, projections of future climate from global models are now being conducted at finer scales (with resolution on the order of 15 miles), providing more realistic characterization of intense weather systems, including hurricanes. For the first time in the NCA process, sea level rise projections incorporate geographic variation based on factors such as local land subsidence, ocean currents, and changes in Earth's gravitational field (see CSSR, Chs. 9 and 12).

Ocean and Coastal Waters: Ocean acidification, warming, and oxygen loss are all increasing, and scientific understanding of the severity of their impacts is growing. Both oxygen loss and acidification may be magnified in some U.S. coastal waters relative to the global average, raising the risk of serious ecological and economic consequences (see CSSR, Chs. 2 and 13).

Rapid Changes for Ice on Earth: New observations from many different sources confirm that ice loss across the globe is continuing and, in many cases, accelerating. Since NCA3, Antarctica and Greenland have continued to lose ice mass, with mounting evidence that mass loss is accelerating. Observations continue to show declines in the volume of

mountain glaciers around the world. Annual September minimum sea ice extent in the Arctic Ocean has decreased at a rate of 11%–16% per decade since the early 1980s, with accelerating ice loss since 2000. The annual sea ice extent minimum for 2016 was the second lowest on record; the sea ice minimums in 2014 and 2015 were also among the lowest on record (see CSSR, Chs. 1, 11, and 12).

Potential Surprises: Both large-scale shifts in the climate system (sometimes called "tipping points") and compound extremes have the potential to generate outcomes that are difficult to anticipate and may have high consequences. The more the climate changes, the greater the potential for these surprises (see CSSR, Ch. 15).

Extreme Events

Climate change is altering the characteristics of many extreme weather and climate-related events. Some extreme events have already become more frequent, intense, widespread, or of longer duration, and many are expected to continue to increase or worsen, presenting substantial challenges for built, agricultural, and natural systems. Some storm types such as hurricanes, tornadoes, and winter storms are also exhibiting changes that have been linked to climate change, although the current state of the science does not yet permit detailed understanding (see CSSR, Executive Summary). Individual extreme weather and climate-related events—even those that have not been clearly attributed to climate change by scientific analyses—reveal risks to society and vulnerabilities that mirror those we expect in a warmer world. Non-climate stressors (such as land-use changes and shifting demographics) can also amplify the damages associated with extreme events. The National Oceanic and Atmospheric Administration estimates that the United States has experienced 44 billion-dollar weather and climate disasters since 2015 (through April 6, 2018), incurring costs of nearly $400 billion (https://www.ncdc.noaa.gov/billions/).

Hurricanes: The 2017 Atlantic Hurricane season alone is estimated to have caused more than $250 billion in damages and over 250 deaths throughout the U.S. Caribbean, Southeast, and Southern Great Plains. More than 30 inches of rain fell during Hurricane Harvey, affecting 6.9 million people. Hurricane Maria's high winds caused widespread devastation to Puerto Rico's transportation, agriculture, communication, and energy infrastructure. Extreme rainfall of up to 37 inches caused widespread flooding and mudslides across the island. The interruption to commerce and standard living conditions will be sustained for a long period while much of Puerto Rico's infrastructure is rebuilt. Hurricane Irma destroyed 25% of buildings in the Florida Keys.

Damage from Hurricane Maria in San Juan, Puerto Rico

Photo taken during a reconnaissance flight of the island on September 23, 2017. *Photo credit: Sgt. Jose Ahiram Diaz-Ramos, Puerto Rico National Guard.*

Floods: In August 2016, a historic flood resulting from 20 to 30 inches of rainfall over several days devastated a large area of southern Louisiana, causing over $10 billion in damages and 13 deaths. More than 30,000 people were rescued from floodwaters that damaged or destroyed more than 50,000 homes, 100,000 vehicles, and 20,000 businesses. In June 2016, torrential rainfall caused destructive flooding throughout many West Virginia towns, damaging thousands of homes and businesses and causing considerable loss of life. More than 1,500 roads and bridges were damaged or destroyed. The 2015–2016 El Niño poured 11 days of record-setting rainfall on Hawai'i, causing severe urban flooding.

Drought: In 2015, drought conditions caused about $5 billion in damages across the Southwest and Northwest, as well as parts of the Northern Great Plains. California experienced the most severe drought conditions. Hundreds of thousands of acres of farmland remained fallow, and excess groundwater pumping was required to irrigate existing agricultural interests. Two years later, in 2017, extreme drought caused $2.5 billion in agricultural damages across the Northern Great Plains. Field crops, including wheat, were severely damaged, and the lack of feed for cattle forced ranchers to sell off livestock.

Wildfires: During the summer of 2015, over 10.1 million acres—an area larger than the entire state of Maryland—burned across the United States, surpassing 2006 for the highest

The Deadly Carr Fire

The Carr Fire (as seen over Shasta County, California, on August 4, 2018) damaged or destroyed more than 1,500 structures and resulted in several fatalities. *Photo credit: Sgt. Lani O. Pascual, U.S. Army National Guard.*

annual total of U.S. acreage burned since record keeping began in 1960. These wildfire conditions were exacerbated by the preceding drought conditions in several states. The most extensive wildfires occurred in Alaska, where 5 million acres burned within the state. In Montana, wildfires burned in excess of 1 million acres. The costliest wildfires occurred in California, where more than 2,500 structures were destroyed by the Valley and Butte Fires; insured losses alone exceeded $1 billion. In October 2017, a historic firestorm damaged or destroyed more than 15,000 homes, businesses, and other structures across California (see Figure 1.5). The Tubbs, Atlas, Nuns, and Redwood Valley Fires caused a total of 44 deaths, and their combined destruction represents the costliest wildfire event on record.

Tornadoes: In March 2017, a severe tornado outbreak caused damage across much of the Midwest and into the Northeast. Nearly 1 million customers lost power in Michigan alone due to sustained high winds, which affected several states from Illinois to New York.

Heat Waves: Honolulu experienced 24 days of record-setting heat during the 2015–2016 El Niño event. As a result, the local energy utility issued emergency public service announcements to curtail escalating air conditioning use that threatened the electrical grid.

New Aspects of This Report

Hundreds of states, counties, cities, businesses, universities, and other entities are implementing actions that build resilience to climate-related impacts and risks, while also aiming to reduce greenhouse gas emissions. Many of these actions have been informed by new climate-related tools and products developed through the U.S. Global Change Research Program (USGCRP) since NCA3 (see Appendix 3: Scenario Products and Data Tools); we briefly highlight a few of them here. In addition, several structural changes have been introduced to the report and new methods used in response to stakeholder needs for more localized information and to address key gaps identified in NCA3. The Third National Climate Assessment remains a valuable and relevant resource—this report expands upon our knowledge and experience as presented four years ago.

Climate Science Special Report: Early in the development of NCA4, experts and Administration officials recognized that conducting a comprehensive physical science assessment (Volume I) in advance of an impacts assessment (Volume II) would allow one to inform the other. The *Climate Science Special Report*, released in November 2017, is Volume I of NCA4 and represents the most thorough and up-to-date assessment of climate science in the United States and underpins the findings of this report; its findings are summarized in Chapter 2 (Our Changing Climate). See the "Key Scientific Advances" section in this box and Box 2.3 in Chapter 2 for more detail.

Scenario Products: As described in more detail in Appendix 3 (Data Tools & Scenario Products), federal interagency groups developed a suite of high-resolution scenario products that span a range of plausible future changes in key environmental variables through at least 2100. These USGCRP scenario products help ensure consistency across the report and improve the ability to synthesize across chapters. Where possible, authors have used these scenario products to frame uncertainty in future climate as it relates to the risks that are the focus of their chapters. In addition, the Indicators Interagency Working Group has developed an Indicators platform that uses observations or calculations to monitor conditions or trends in the earth system, just as businesses might use the unemployment index as an indicator of economic conditions (see Figure 1.2 and https://www.globalchange.gov/browse/indicators).

Localized Information: With the increased focus on local and regional information in NCA4, USGCRP agencies developed two additional products that not only inform this assessment but can serve as valuable decision-support tools. The first are the State Climate Summaries—a peer-reviewed collection of climate change information covering all ten NCA4 regions at the state level. In addition to standard data on observed and projected climate change, each State Climate Summary contains state-specific changes and their related impacts as well as a suite of complementary graphics (stateclimatesummaries.globalchange.gov). The second product is the U.S. Climate Resilience Toolkit (https://toolkit.climate.gov/), which offers data-driven tools, information, and subject-matter expertise from across the Federal Government in one easy-to-use location, so Americans are better able to understand the climate-related risks and opportunities impacting their communities and can make more informed decisions on how to respond. In particular, the case studies showcase examples of climate change impacts and accompanying response actions that complement those presented in Figure 1.1 and allow communities to learn how to build resilience from one another.

New Chapters: In response to public feedback on NCA3 and input solicited in the early stages of this assessment, a number of significant structural changes have been made. Most fundamentally, the balance of the report's focus has shifted from national-level chapters to regional chapters in response to a growing desire for more localized information on impacts. Building on this theme, the Great Plains chapter has been split into Northern and Southern chapters (Chapters 22 and 23) along the Kansas–Nebraska border. In addition, the U.S. Caribbean is now featured as a separate region in this report (Chapter 20), focusing on the unique impacts, risks, and response capabilities in Puerto Rico and the U.S. Virgin Islands.

Public input also requested greater international context in the report, which has been addressed through two new additions. A new chapter focuses on topics including the effects of climate change on U.S. trade and businesses, national security, and U.S. humanitarian assistance and disaster relief (Chapter 16). A new international appendix (Appendix 4) presents a number of illustrative examples of how other countries have conducted national climate assessments, putting our own effort into a global context.

Given recent scientific advances, some emerging topics warranted a more visible platform in NCA4. A new chapter on Air Quality (Chapter 13) examines how traditional air pollutants are affected by climate change. A new chapter on Sector Interactions, Multiple Stressors, and Complex Systems (Chapter 17) evaluates climate-related risks to interconnected human and natural systems that are increasingly vulnerable to cascading impacts and highlights advances in analyzing how these systems will interact with and respond to a changing environment (see Box 1.3).

Integrating Economics: This report, to a much greater degree than previous National Climate Assessments, includes broader and more systematic quantification of climate change impacts in economic terms. While this is an emerging body of literature that is not yet reflected in each of the 10 NCA regions, it represents a valuable advancement in our understanding of the financial costs and benefits of climate change impacts. Figure 1.21 provides an illustration of the type of economic information that is integrated throughout this report. It shows the financial damages *avoided* under a lower scenario (RCP4.5) versus a higher scenario (RCP8.5).

New Economic Impact Studies

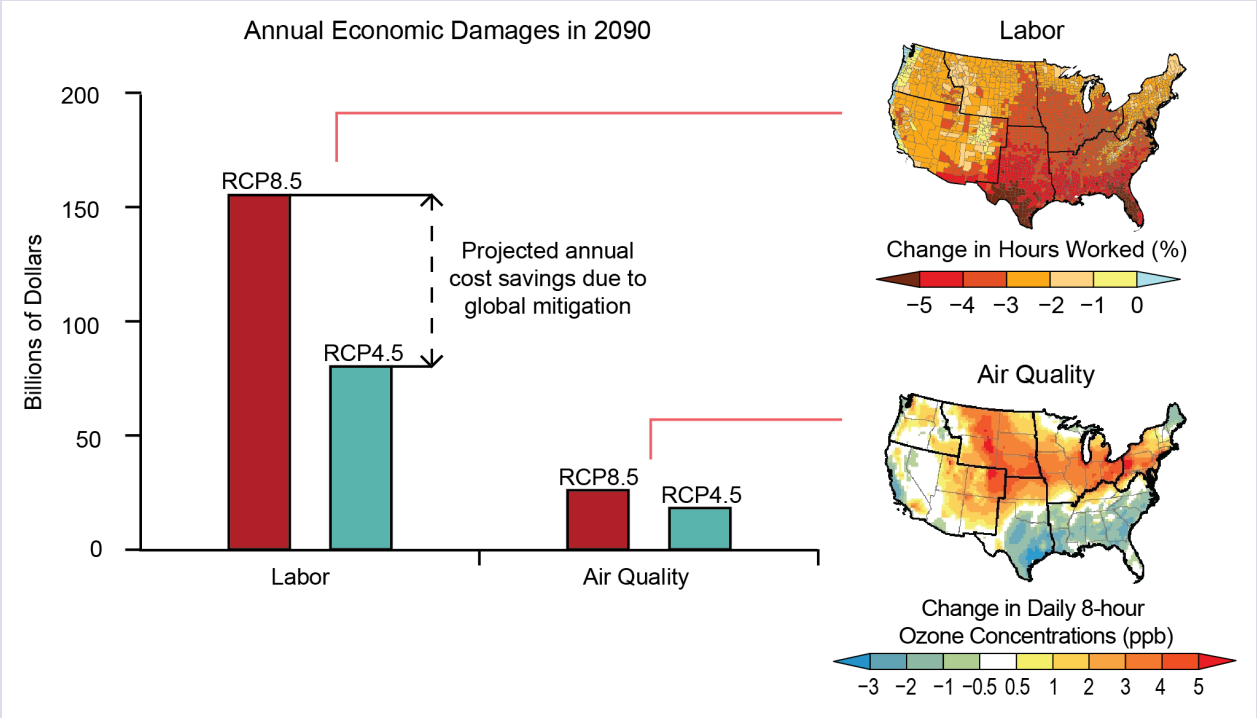
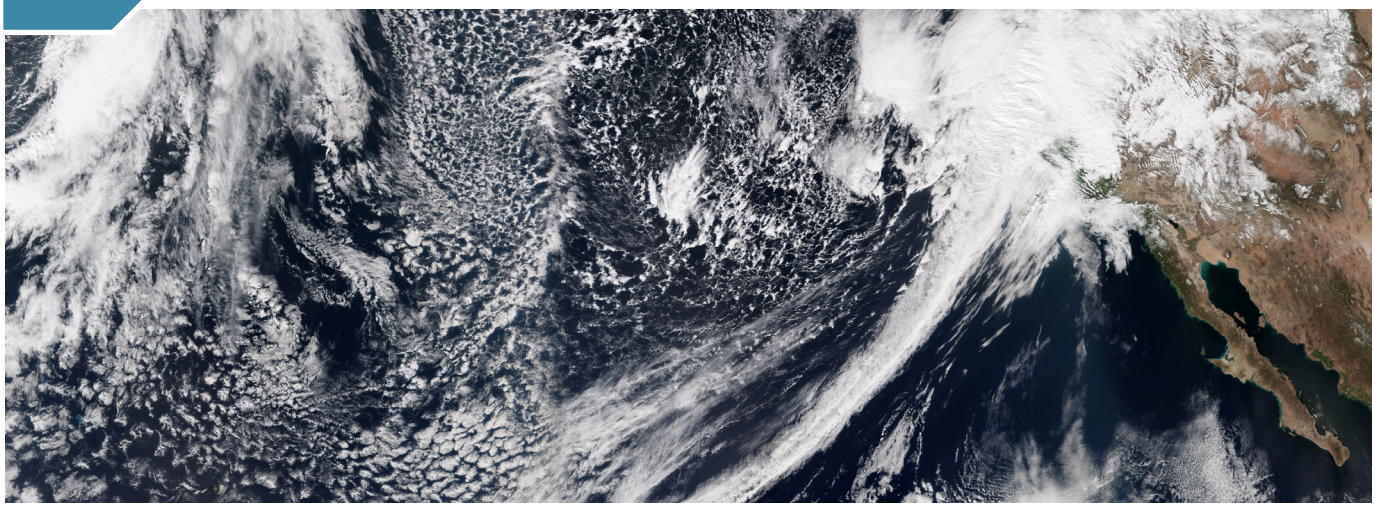


Figure 1.21: Annual economic impact estimates are shown for labor and air quality. The bar graph on the left shows national annual damages in 2090 (in billions of 2015 dollars) for a higher scenario (RCP8.5) and lower scenario (RCP4.5); the difference between the height of the RCP8.5 and RCP4.5 bars for a given category represents an estimate of the economic benefit to the United States from global mitigation action. For these two categories, damage estimates do not consider costs or benefits of new adaptation actions to reduce impacts, and they do not include Alaska, Hawai'i and U.S.-Affiliated Pacific Islands, or the U.S. Caribbean. The maps on the right show regional variation in annual impacts projected under the higher scenario (RCP8.5) in 2090. The map on the top shows the percent change in hours worked in high-risk industries as compared to the period 2003–2007. The hours lost result in economic damages: for example, $28 billion per year in the Southern Great Plains. The map on the bottom is the change in summer-average maximum daily 8-hour ozone concentrations (ppb) at ground-level as compared to the period 1995–2005. These changes in ozone concentrations result in premature deaths: for example, an additional 910 premature deaths each year in the Midwest. *Source: EPA, 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17-001.*

National Topics

Executive Summaries

2 Our Changing Climate



An atmospheric river pours moisture into the western United States in February 2017.

Key Message 1

Observed Changes in Global Climate

Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8°F from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.

Key Message 2

Future Changes in Global Climate

Earth's climate will continue to change over this century and beyond. Past mid-century, how much the climate changes will depend primarily on global emissions of greenhouse gases and on the response of Earth's climate system to human-induced warming. With significant reductions in emissions, global temperature increase could be limited to 3.6°F (2°C) or less compared to preindustrial temperatures. Without significant reductions, annual average global temperatures could increase by 9°F (5°C) or more by the end of this century compared to preindustrial temperatures.

Key Message 3

Warming and Acidifying Oceans

The world's oceans have absorbed 93% of the excess heat from human-induced warming since the mid-20th century and are currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere annually from human activities, making the oceans warmer and more acidic. Increasing sea surface temperatures, rising sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation are contributing to overall declining oxygen concentrations in many locations.

Key Message 4

Rising Global Sea Levels

Global average sea level has risen by about 7–8 inches (about 16–21 cm) since 1900, with almost half this rise occurring since 1993 as oceans have warmed and land-based ice has melted. Relative to the year 2000, sea level is very likely to rise 1 to 4 feet (0.3 to 1.3 m) by the end of the century. Emerging science regarding Antarctic ice sheet stability suggests that, for higher scenarios, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed.

Key Message 5

Increasing U.S. Temperatures

Annual average temperature over the contiguous United States has increased by 1.2ºF (0.7°C) over the last few decades and by 1.8°F (1°C) relative to the beginning of the last century. Additional increases in annual average temperature of about 2.5°F (1.4°C) are expected over the next few decades regardless of future emissions, and increases ranging from 3°F to 12°F (1.6°–6.6°C) are expected by the end of century, depending on whether the world follows a higher or lower future scenario, with proportionally greater changes in high temperature extremes.

Key Message 6

Changing U.S. Precipitation

Annual precipitation since the beginning of the last century has increased across most of the northern and eastern United States and decreased across much of the southern and western United States. Over the coming century, significant increases are projected in winter and spring over the Northern Great Plains, the Upper Midwest, and the Northeast. Observed increases in the frequency and intensity of heavy precipitation events in most parts of the United States are projected to continue. Surface soil moisture over most of the United States is likely to decrease, accompanied by large declines in snowpack in the western United States and shifts to more winter precipitation falling as rain rather than snow.

Key Message 7

Rapid Arctic Change

In the Arctic, annual average temperatures have increased more than twice as fast as the global average, accompanied by thawing permafrost and loss of sea ice and glacier mass. Arctic-wide glacial and sea ice loss is expected to continue; by mid-century, it is very likely that the Arctic will be nearly free of sea ice in late summer. Permafrost is expected to continue to thaw over the coming century as well, and the carbon dioxide and methane released from thawing permafrost has the potential to amplify human-induced warming, possibly significantly.

Key Message 8

Changes in Severe Storms

Human-induced change is affecting atmospheric dynamics and contributing to the poleward expansion of the tropics and the northward shift in Northern Hemisphere winter storm tracks since 1950. Increases in greenhouse gases and decreases in air pollution have contributed to increases in Atlantic hurricane activity since 1970. In the future, Atlantic and eastern North Pacific hurricane rainfall and intensity are projected to increase, as are the frequency and severity of landfalling "atmospheric rivers" on the West Coast.

Key Message 9

Increases in Coastal Flooding

Regional changes in sea level rise and coastal flooding are not evenly distributed across the United States; ocean circulation changes, sinking land, and Antarctic ice melt will result in greater-than-average sea level rise for the Northeast and western Gulf of Mexico under lower scenarios and most of the U.S. coastline other than Alaska under higher scenarios. Since the 1960s, sea level rise has already increased the frequency of high tide flooding by a factor of 5 to 10 for several U.S. coastal communities. The frequency, depth, and extent of tidal flooding are expected to continue to increase in the future, as is the more severe flooding associated with coastal storms, such as hurricanes and nor'easters.

Key Message 10

Long-Term Changes

The climate change resulting from human-caused emissions of carbon dioxide will persist for decades to millennia. Self-reinforcing cycles within the climate system have the potential to accelerate human-induced change and even shift Earth's climate system into new states that are very different from those experienced in the recent past. Future changes outside the range projected by climate models cannot be ruled out, and due to their systematic tendency to underestimate temperature change during past warm periods, models may be more likely to underestimate than to overestimate long-term future change.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/climate.

3 Water

Levee repair along the San Joaquin River in California, February 2017

Key Message 1

Changes in Water Quantity and Quality

Significant changes in water quantity and quality are evident across the country. These changes, which are expected to persist, present an ongoing risk to coupled human and natural systems and related ecosystem services. Variable precipitation and rising temperature are intensifying droughts, increasing heavy downpours, and reducing snowpack. Reduced snow-to-rain ratios are leading to significant differences between the timing of water supply and demand. Groundwater depletion is exacerbating drought risk. Surface water quality is declining as water temperature increases and more frequent high-intensity rainfall events mobilize pollutants such as sediments and nutrients.

Key Message 2

Deteriorating Water Infrastructure at Risk

Deteriorating water infrastructure compounds the climate risk faced by society. Extreme precipitation events are projected to increase in a warming climate and may lead to more severe floods and greater risk of infrastructure failure in some regions. Infrastructure design, operation, financing principles, and regulatory standards typically do not account for a changing climate. Current risk management does not typically consider the impact of compound extremes (co-occurrence of multiple events) and the risk of cascading infrastructure failure.

Key Message 3

Water Management in a Changing Future

Water management strategies designed in view of an evolving future we can only partially anticipate will help prepare the Nation for water- and climate-related risks of the future. Current water management and planning principles typically do not address risk that changes over time, leaving society exposed to more risk than anticipated. While there are examples of promising approaches to manage climate risk, the gap between research and implementation, especially in view of regulatory and institutional constraints, remains a challenge.

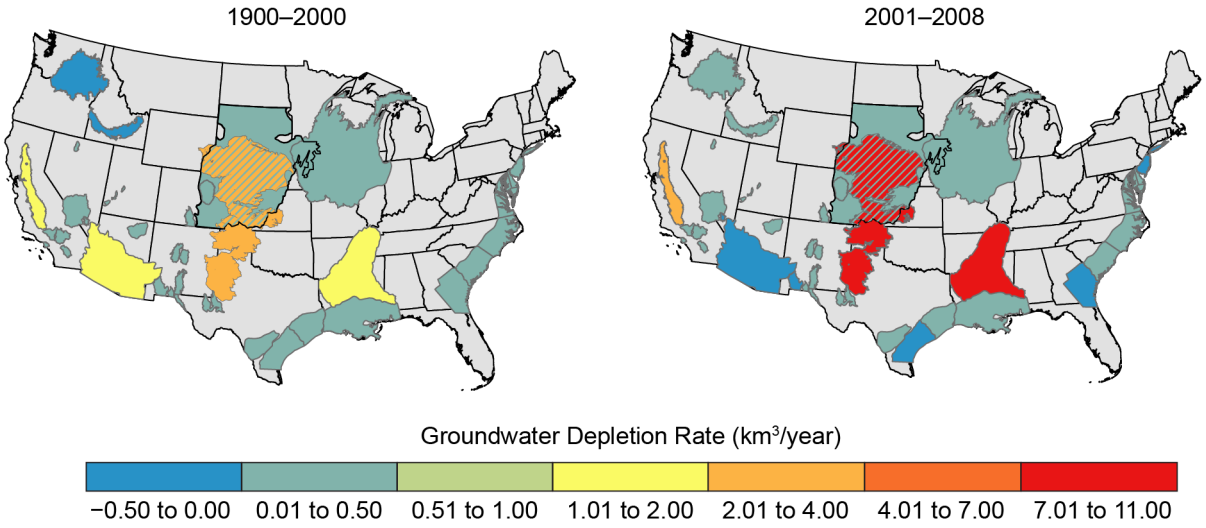
Ensuring a reliable supply of clean freshwater to individuals, communities, and ecosystems, together with effective management of floods and droughts, is the foundation of human and ecological health. The water sector is also central to the economy and contributes significantly to the resilience of many other sectors, including agriculture, energy, urban environments, and industry.

Water systems face considerable risk, even without anticipated future climate changes. Limited surface water storage, as well as a limited ability to make use of long-term drought forecasts and to trade water across uses and basins, has led to a significant depletion of aquifers in many regions in the United States. Across the Nation, much of the critical water and wastewater infrastructure is nearing the end of its useful life. To date, no comprehensive assessment exists of the climate-related vulnerability of U.S. water infrastructure (including dams, levees, aqueducts, sewers, and water and wastewater distribution and treatment systems), the potential resulting damages, or the cost of reconstruction and recovery. Paleoclimate information (reconstructions of past climate derived from ice cores or tree rings) shows that over the last 500 years, North America has experienced pronounced wet/dry regime shifts that sometimes persisted for decades. Because such protracted exposures to extreme floods or droughts in different parts of the country are extraordinary compared to events experienced in the 20th century, they are not yet incorporated in water management principles and practice. Anticipated future climate change will exacerbate this risk in many regions.

A central challenge to water planning and management is learning to plan for plausible future climate conditions that are wider in range than those experienced in the 20th century. Doing so requires approaches that evaluate plans over many possible futures instead of just one, incorporate real-time monitoring and forecast products to better manage extremes when they occur, and update policies and engineering principles with the best available geoscience-based understanding of planetary change. While this represents a break from historical practice, recent examples of adaptation responses undertaken by large water management agencies, including major metropolitan water utilities and the U.S. Army Corps of Engineers, are promising.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/water.

Depletion of Groundwater in Major U.S. Regional Aquifers



(left) Groundwater supplies have been decreasing in the major regional aquifers of the United States over the last century (1900–2000). (right) This decline has accelerated recently (2001–2008) due to persistent droughts in many regions and the lack of adequate surface water storage to meet demands. This decline in groundwater compromises the ability to meet water needs during future droughts and impacts the functioning of groundwater dependent ecosystems (e.g., Kløve et al. 2014).The values shown are net volumetric rates of groundwater depletion (km^3 per year) averaged over each aquifer. Subareas of an aquifer may deplete at faster rates or may be actually recovering. Hatching in the figure represents where the High Plains Aquifer overlies the deep, confined Dakota Aquifer. *From Figure 3.2 (Source: adapted from Konikow 2015. Reprinted from Groundwater with permission of the National Groundwater Association. © 2015).*

4 Energy Supply, Delivery, and Demand

Linemen working to restore power in Puerto Rico after Hurricane Maria in 2017

Key Message 1

Nationwide Impacts on Energy

The Nation's energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances. The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy. Cascading impacts on other critical sectors could affect economic and national security.

Key Message 2

Changes in Energy System Affect Vulnerabilities

Changes in energy technologies, markets, and policies are affecting the energy system's vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities. Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience.

The Nation's economic security is increasingly dependent on an affordable and reliable supply of energy. Every sector of the economy depends on energy, from manufacturing to agriculture, banking, healthcare, telecommunications, and transportation. Increasingly, climate change and extreme weather events are affecting the energy system, threatening more frequent and longer-lasting power outages and fuel shortages. Such events can have cascading impacts on other critical sectors, potentially affecting the Nation's economic and national security. At the same time, the energy sector is undergoing substantial policy, market, and technology-driven changes that are projected to affect these vulnerabilities.

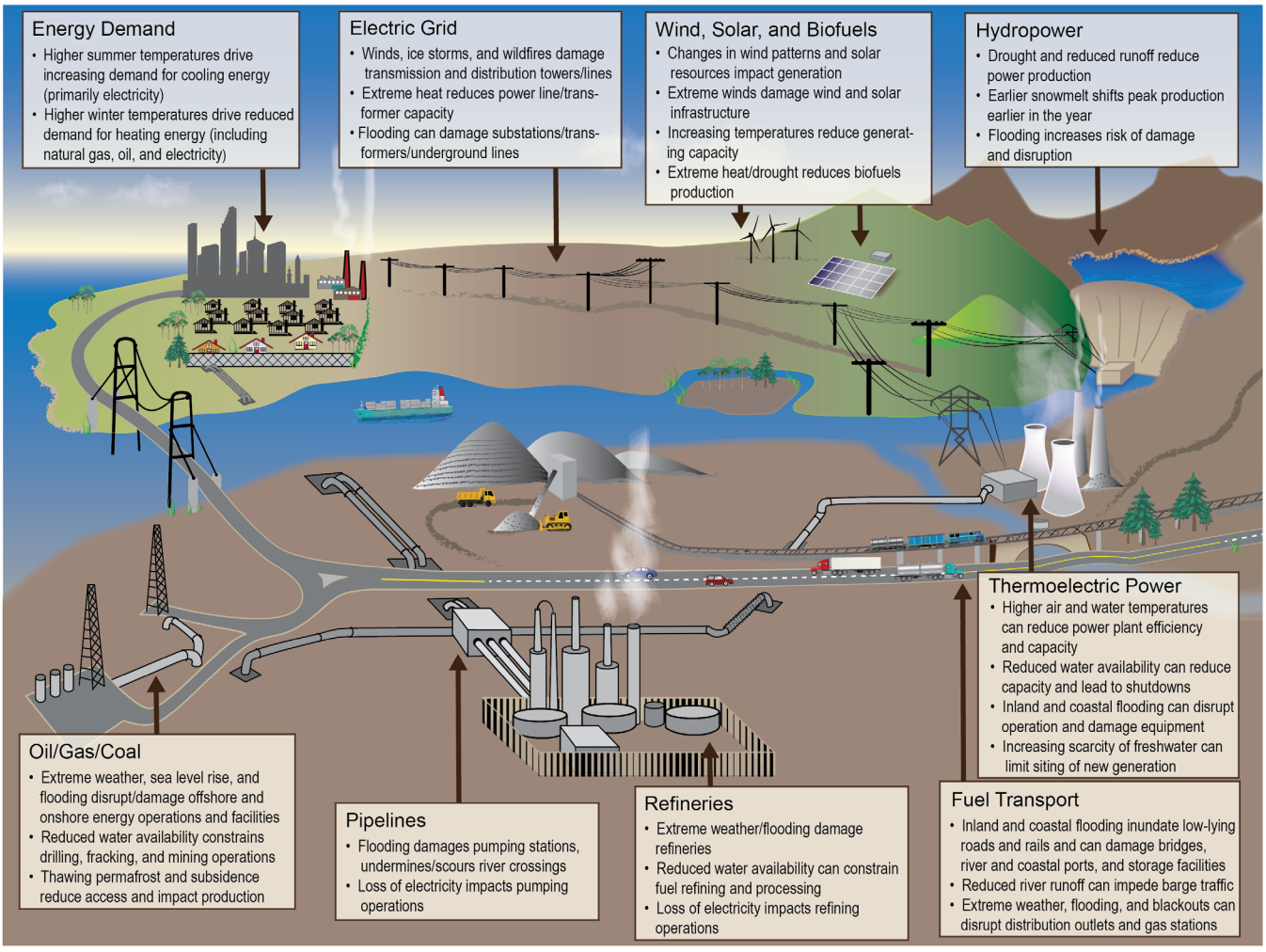
The impacts of extreme weather and climate change on energy systems will differ across the United States. Low-lying energy facilities and systems located along inland waters or near the coasts are at elevated risk of flooding from more intense precipitation, rising sea levels, and more intense hurricanes. Increases in the severity and frequency of extreme precipitation are projected to affect inland energy infrastructure in every region. Rising temperatures and extreme heat events are projected to reduce the generation capacity of thermoelectric power plants and decrease the efficiency of the transmission grid. Rising temperatures are projected to also drive greater use of air conditioning and increase electricity demand, likely resulting in increases in electricity costs. The increase in annual electricity demand across the country for cooling is offset only marginally by the relatively small decline in electricity demand for heating. Extreme cold events, including ice and snow events, can damage power lines and impact fuel supplies. Severe drought, along with changes in evaporation, reductions in mountain snowpack, and shifting mountain snowmelt timing, is projected to reduce hydropower production and threaten oil and gas drilling and refining, as well as thermoelectric power plants that rely on surface water for cooling. Drier conditions are projected to increase the risk of wildfires and damage to energy production and generation assets and the power grid.

At the same time, the nature of the energy system itself is changing. Low carbon-emitting natural gas generation has displaced coal generation due to the rising production of low-cost, unconventional natural gas, in part supported by federal investment in research and development. In the last 10 years, the share of generation from natural gas increased from 20% to over 30%, while coal has declined from nearly 50% to around 30%. Over this same time, generation from wind and solar has grown from less than 1% to over 5% due to a combination of technological progress, dramatic cost reductions, and federal and state policies.

It is possible to address the challenges of a changing climate and energy system, and both industry and governments at the local, state, regional, federal, and tribal levels are taking actions to improve the resilience of the Nation's energy system. These actions include planning and operational measures that seek to anticipate climate impacts and prevent or respond to damages more effectively, as well as hardening measures to protect assets from damage during extreme events. Resilience actions can have co-benefits, such as developing and deploying new innovative energy technologies that increase resilience and reduce emissions. While steps are being taken, an escalation of the pace, scale, and scope of efforts is needed to ensure the safe and reliable provision of energy and to establish a climate-ready energy system to address present and future risks.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/energy.

Potential Impacts from Extreme Weather and Climate Change



Extreme weather and climate change can potentially impact all components of the Nation's energy system, from fuel (petroleum, coal, and natural gas) production and distribution to electricity generation, transmission, and demand. *From Figure 4.1 (Source: adapted from DOE 2013)*.

5 Land Cover and Land-Use Change

Agricultural fields near the Ririe Reservoir in Bonneville, Idaho

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere. Reforestation can foster localized cooling, while in urban areas, continued warming is expected to exacerbate urban heat island effects.

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns, species distributions, and the suitability of land for specific uses. The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services.

Climate can affect and be affected by changes in land cover (the physical features that cover the land such as trees or pavement) and land use (human management and activities on land, such as mining or recreation). A forest, for instance, would likely include tree cover but could also include areas of recent tree removals currently covered by open grass areas. Land cover and use are inherently coupled: changes in land-use practices can change land cover, and land cover enables specific land uses. Understanding how land cover, use, condition, and management vary in space and time is challenging.

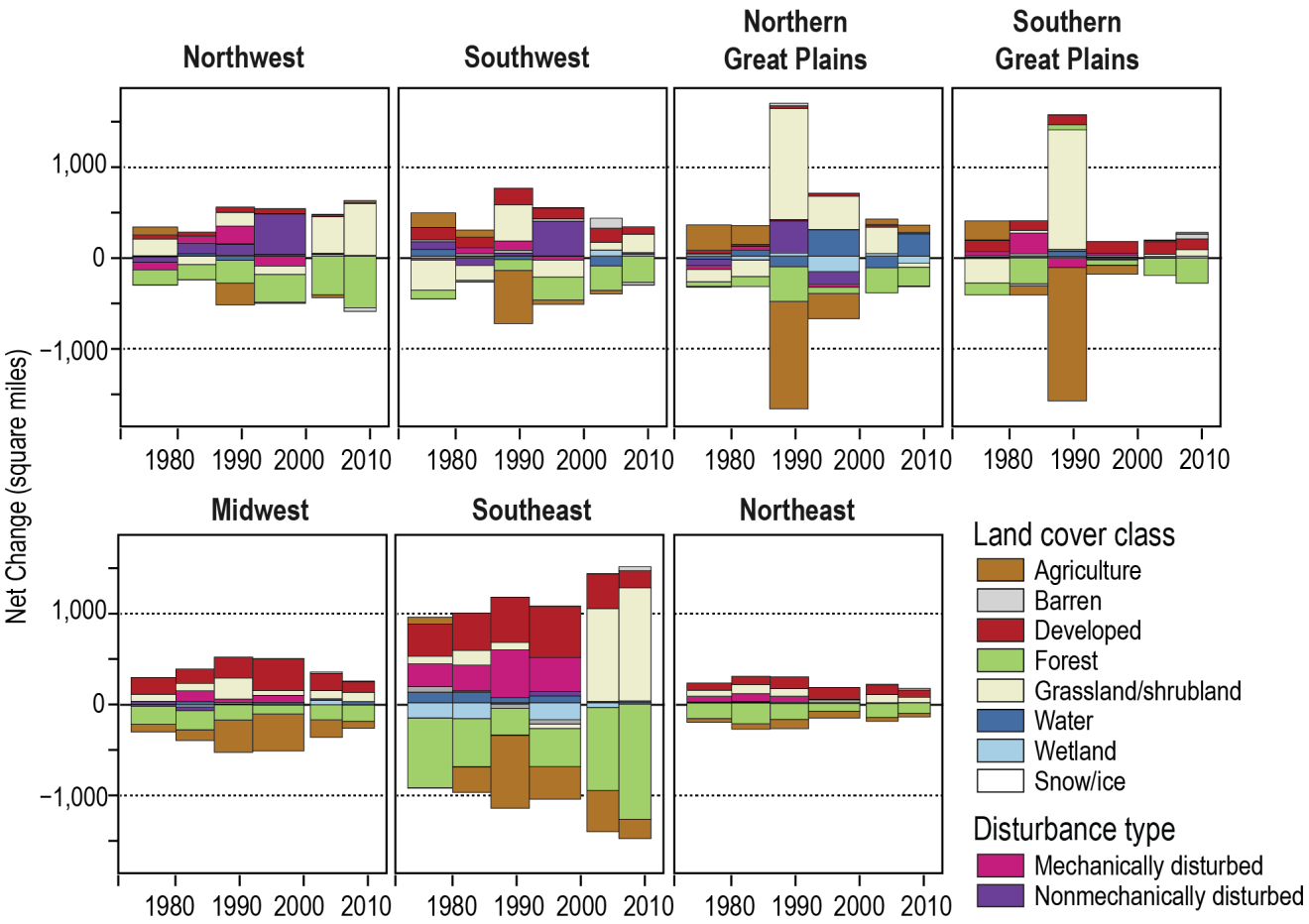
Changes in land cover can occur in response to both human and climate drivers. For example, demand for new settlements often results in the permanent loss of natural and working lands, which can result in localized changes in weather patterns, temperature, and precipitation. Aggregated over large areas, these changes have the potential to influence Earth's climate by altering regional and global circulation patterns, changing the albedo (reflectivity) of Earth's surface, and changing the amount of carbon dioxide (CO_2) in the atmosphere. Conversely, climate change can also influence land cover, resulting in a loss of forest cover from climate-related increases in disturbances, the expansion of woody vegetation into grasslands, and the loss of beaches due to coastal erosion amplified by rises in sea level.

Land use is also changed by both human and climate drivers. Land-use decisions are traditionally based on short-term economic factors. Land-use changes are increasingly being influenced by distant forces due to the globalization of many markets. Land use can also change due to local, state, and national policies, such as programs designed to remove cultivation from highly erodible land to mitigate degradation, legislation to address sea level rise in local comprehensive plans, or policies that reduce the rate of timber harvest on federal lands. Technological innovation has also influenced land-use change, with the expansion of cultivated lands from the development of irrigation technologies and, more recently, decreases in demand for agricultural land due to increases in crop productivity. The recent expansion of oil and gas extraction activities throughout large areas of the United States demonstrates how policy, economics, and technology can collectively influence and change land use and land cover.

Decisions about land use, cover, and management can help determine society's ability to mitigate and adapt to climate change.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/land-changes.

Changes in Land Cover by Region



The figure shows the net change in land cover by class in square miles, from 1973 to 2011. Land-cover change has been highly dynamic over space, time, and sector, in response to a range of driving forces. Net change in land cover reveals the trajectory of a class over time. A dramatic example illustrated here is the large decline in agricultural lands in the two Great Plains regions beginning in the mid-1980s, which resulted in large part from the establishment of the Conservation Reserve Program. Over the same period, agriculture also declined in the Southwest region; however, the net decline was largely attributable to prolonged drought conditions, as opposed to changes in federal policy. Data for the period 1973–2000 are from Sleeter et al. (2013) while data from 2001–2011 are from the National Land Cover Database (NLCD). Note: the two disturbance categories used for the 1973–2000 data were not included in the NLCD data for 2001–2011 and largely represent conversions associated with harvest activities (mechanical disturbance) and wildfire (nonmechanical disturbance). Comparable data are unavailable for the U.S. Caribbean, Alaska, and Hawai'i & U.S.-Affiliated Pacific Islands regions, precluding their representation in this figure. *From Figure 5.2 (Source: USGS).*

6 Forests

California's multiyear drought killed millions of trees in low-elevation forests

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries).

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances. The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions.

Key Message 3

Adaptation

Forest management activities that increase the resilience of U.S. forests to climate change are being implemented, with a broad range of adaptation options for different resources, including applications in planning. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation.

Forests on public and private lands provide benefits to the natural environment, as well as economic benefits and ecosystem services to people in the United States and globally. The ability of U.S. forests to continue to provide goods and services is threatened by climate change and associated increases in extreme events and disturbances. For example, severe drought and insect outbreaks have killed hundreds of millions of trees across the United States over the past 20 years, and wildfires have burned at least 3.7 million acres annually in all but 3 years from 2000 to 2016. Recent insect-caused mortality appears to be outside the historical context and is likely related to climate change; however, it is unclear if the apparent climate-related increase in fire-caused tree mortality is outside the range of what has been observed over centuries of wildfire occurrence.

A warmer climate will decrease tree growth in most forests that are water limited (for example, low-elevation ponderosa pine forests) but will likely increase growth in forests that are energy limited (for example, subalpine forests, where long-lasting snowpack and cold temperatures limit the growing season). Drought and extreme high temperatures can cause heat-related stress in vegetation and, in turn, reduce forest productivity and increase mortality. The rate of climate warming is likely to influence forest health (that is, the extent to which ecosystem processes are functioning within their range of historic variation) and competition between trees, which will affect the distributions of some species.

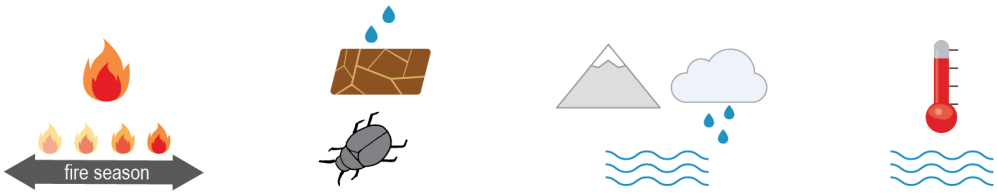
Large-scale disturbances (over thousands to hundreds of thousands of acres) that cause rapid change (over days to years) and more gradual climate change effects (over decades) will alter the ability of forests to provide ecosystem services, although alterations will vary greatly depending on the tree species and local biophysical conditions. For example, whereas crown fires (forest fires that spread from treetop to treetop) will cause extensive areas of tree mortality in dense, dry forests in the western United States that have not experienced wildfire for several decades, increased fire frequency is expected to facilitate the persistence of sprouting hardwood species such as quaking aspen in western mountains and fire tolerant pine and hardwood species in the eastern United States (see regional chapters for more detail on variation across the United States). Drought, heavy rainfall, altered snowpack, and changing forest conditions are increasing the frequency of low summer streamflow, winter and spring flooding, and low water quality in some locations, with potential negative impacts on aquatic resources and on water supplies for human communities.

From 1990 to 2015, U.S. forests sequestered 742 teragrams (Tg) of carbon dioxide (CO_2) per year, offsetting approximately 11% of the Nation's CO_2 emissions. U.S. forests are projected to continue to store carbon but at declining rates, as affected by both land use and lower CO_2 uptake as forests get older. However, carbon accumulation in surface soils (at depths of 0–4 inches) can mitigate the declining carbon sink of U.S. forests if reforestation is routinely implemented at large spatial scales.

Implementation of climate-informed resource planning and management on forestlands has progressed significantly over the past decade. The ability of society and resource management to continue to adapt to climate change will be determined primarily by socioeconomic factors and organizational capacity. A viable forest-based workforce can facilitate timely actions that minimize negative effects of climate change. Ensuring the continuing health of forest ecosystems and, where desired and feasible, keeping forestland in forest cover are key challenges for society.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/forests.

Climate Change Vulnerabilities and Adaptation Options



Climate Change Vulnerabilities	Increasing wildfire area burned and fire season length	Increasing drought severity and incidence of insect outbreaks	Lower snowpack, increasing precipitation intensity, and higher winter peakflows	Lower summer streamflows and increasing stream temperatures
Adaptation Options	Reduce hazardous fuels with prescribed burning and managed wildfire	Reduce forest stand density to increase tree vigor; plant drought-tolerant species and genotypes	Implement designs for forest road systems that consider increased flooding hazard	Use mapping of projected stream temperatures to set priorities for riparian restoration and coldwater fish conservation

To increase resilience to future stressors and disturbances, examples of adaptation options (risk management) have been developed in response to climate change vulnerabilities in forest ecosystems (risk assessment) in the Pacific Northwest. Vulnerabilities and adaptation options vary among different forest ecosystems. *From Figure 6.7 (Sources: U.S. Forest Service and University of Washington).*

7 Ecosystems, Ecosystem Services, and Biodiversity

Kodiak National Wildlife Refuge, Alaska

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways. Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges. Local and global extinctions may occur when climate change outpaces the capacity of species to adapt.

Key Message 2

Impacts on Ecosystems

Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment. These changes are reconfiguring ecosystems in unprecedented ways.

Key Message 3

Ecosystem Services at Risk

The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems. Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring.

Key Message 4

Challenges for Natural Resource Management

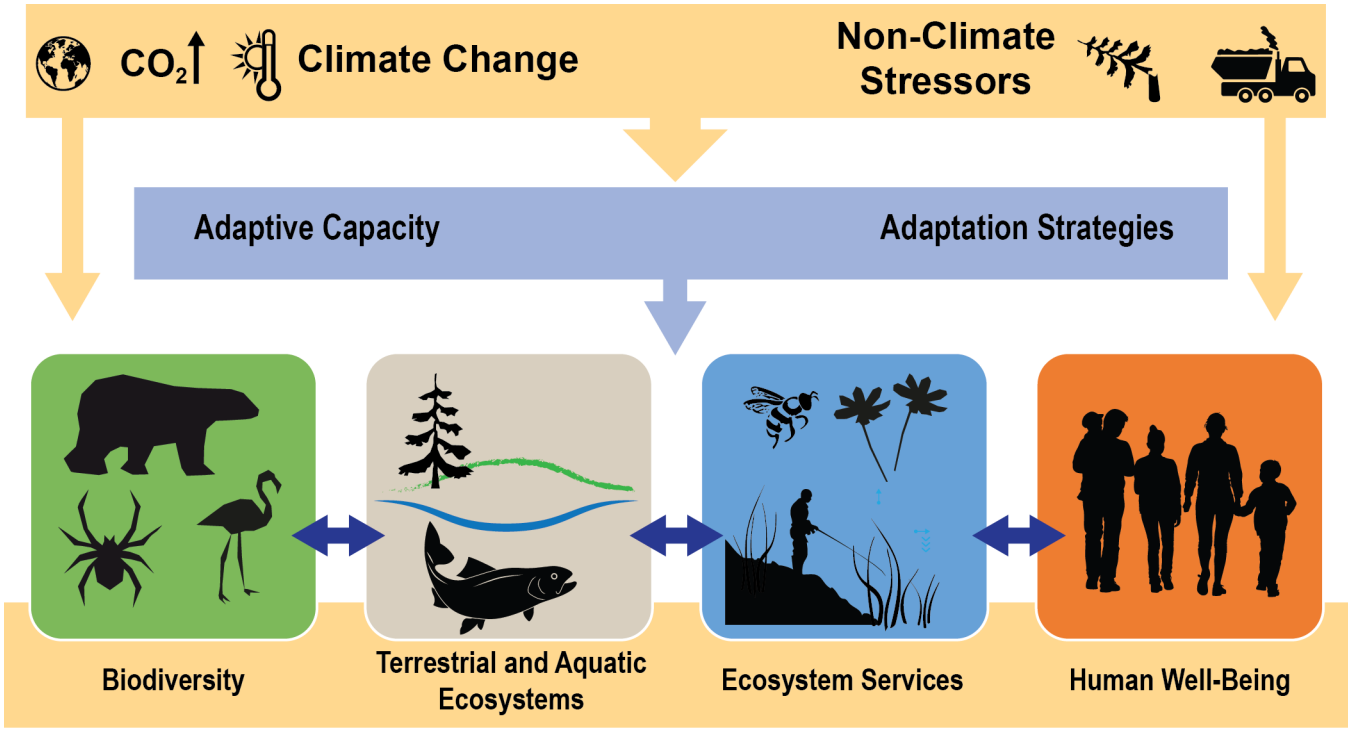
Traditional natural resource management strategies are increasingly challenged by the impacts of climate change. Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

Biodiversity—the variety of life on Earth—provides vital services that support and improve human health and well-being. Ecosystems, which are composed of living things that interact with the physical environment, provide numerous essential benefits to people. These benefits, termed ecosystem services, encompass four primary functions: provisioning materials, such as food and fiber; regulating critical parts of the environment, such as water quality and erosion control; providing cultural services, such as recreational opportunities and aesthetic value; and providing supporting services, such as nutrient cycling. Climate change poses many threats and potential disruptions to ecosystems and biodiversity, as well as to the ecosystem services on which people depend.

Building on the findings of the Third National Climate Assessment (NCA3), this chapter provides additional evidence that climate change is significantly impacting ecosystems and biodiversity in the United States. Mounting evidence also demonstrates that climate change is increasingly compromising the ecosystem services that sustain human communities, economies, and well-being. Both human and natural systems respond to change, but their ability to respond and thrive under new conditions is determined by their adaptive capacity, which may be inadequate to keep pace with rapid change. Our understanding of climate change impacts and the responses of biodiversity and ecosystems has improved since NCA3. The expected consequences of climate change will vary by region, species, and ecosystem type. Management responses are evolving as new tools and approaches are developed and implemented; however, they may not be able to overcome the negative impacts of climate change. Although efforts have been made since NCA3 to incorporate climate adaptation strategies into natural resource management, significant work remains to comprehensively implement climate-informed planning. This chapter presents additional evidence for climate change impacts to biodiversity, ecosystems, and ecosystem services, reflecting increased confidence in the findings reported in NCA3. The chapter also illustrates the complex and interrelated nature of climate change impacts to biodiversity, ecosystems, and the services they provide.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/ecosystems.

Climate Change, Ecosystems, and Ecosystem Services



Climate and non-climate stressors interact synergistically on biological diversity, ecosystems, and the services they provide for human well-being. The impact of these stressors can be reduced through the ability of organisms to adapt to changes in their environment, as well as through adaptive management of the resources upon which humans depend. Biodiversity, ecosystems, ecosystem services, and human well-being are interconnected: biodiversity underpins ecosystems, which in turn provide ecosystem services; these services contribute to human well-being. Ecosystem structure and function can also influence the biodiversity in a given area. The use of ecosystem services by humans, and therefore the well-being humans derive from these services, can have feedback effects on ecosystem services, ecosystems, and biodiversity. *From Figure 7.1 (Sources: NOAA, USGS, and DOI).*

8 Coastal Effects

Natural “green barriers” help protect this Florida coastline and infrastructure from severe storms and floods.

Key Message 1

Coastal Economies and Property Are Already at Risk

America’s trillion-dollar coastal property market and public infrastructure are threatened by the ongoing increase in the frequency, depth, and extent of tidal flooding due to sea level rise, with cascading impacts to the larger economy. Higher storm surges due to sea level rise and the increased probability of heavy precipitation events exacerbate the risk. Under a higher scenario (RCP8.5), many coastal communities will be transformed by the latter part of this century, and even under lower scenarios (RCP4.5 or RCP2.6), many individuals and communities will suffer financial impacts as chronic high tide flooding leads to higher costs and lower property values. Actions to plan for and adapt to more frequent, widespread, and severe coastal flooding would decrease direct losses and cascading economic impacts.

Key Message 2

Coastal Environments Are Already at Risk

Fisheries, tourism, human health, and public safety depend on healthy coastal ecosystems that are being transformed, degraded, or lost due in part to climate change impacts, particularly sea level rise and higher numbers of extreme weather events. Restoring and conserving coastal ecosystems and adopting natural and nature-based infrastructure solutions can enhance community and ecosystem resilience to climate change, help to ensure their health and vitality, and decrease both direct and indirect impacts of climate change.

Key Message 3

Social Challenges Intensified

As the pace and extent of coastal flooding and erosion accelerate, climate change impacts along our coasts are exacerbating preexisting social inequities, as communities face difficult questions about determining who will pay for current impacts and future adaptation and mitigation strategies and if, how, or when to relocate. In response to actual or projected climate change losses and damages, coastal communities will be among the first in the Nation to test existing climate-relevant legal frameworks and policies against these impacts and, thus, will establish precedents that will affect both coastal and non-coastal regions.

The Coasts chapter of the Third National Climate Assessment, published in 2014, focused on coastal lifelines at risk, economic disruption, uneven social vulnerability, and vulnerable ecosystems. This Coastal Effects chapter of the Fourth National Climate Assessment updates those themes, with a focus on integrating the socioeconomic and environmental impacts and consequences of a changing climate. Specifically, the chapter builds on the threat of rising sea levels exacerbating tidal and storm surge flooding, the state of coastal ecosystems, and the treatment of social vulnerability by introducing the implications for social equity.

U.S. coasts are dynamic environments and economically vibrant places to live and work. As of 2013, coastal shoreline counties were home to 133.2 million people, or 42% of the population. The coasts are economic engines that support jobs in defense, fishing, transportation, and tourism industries; contribute substantially to the U.S. gross domestic product; and serve as hubs of commerce, with seaports connecting the country with global trading partners. Coasts are home to diverse ecosystems such as beaches, intertidal zones, reefs, seagrasses, salt marshes, estuaries, and deltas that support a range of important services including fisheries, recreation, and coastal storm protection. U.S. coasts span three oceans, as well as the Gulf of Mexico, the Great Lakes, and Pacific and Caribbean islands.

The social, economic, and environmental systems along the coasts are being affected by climate change. Threats from sea level rise (SLR) are exacerbated by dynamic processes such as high tide and storm surge flooding (Ch. 19: Southeast, KM 2), erosion (Ch. 26: Alaska, KM 2), waves and their effects, saltwater intrusion into coastal aquifers and elevated groundwater tables (Ch. 27: Hawai'i & Pacific Islands, KM 1; Ch. 3: Water, KM 1), local rainfall (Ch. 3: Water, KM 1), river runoff (Ch. 3: Water, KM 1), increasing water and surface air temperatures (Ch. 9: Oceans, KM 3), and ocean acidification (see Ch. 2: Climate, KM 3 and Ch. 9: Oceans, KM 1, 2, and 3 for more information on ocean acidification, hypoxia, and ocean warming).

Although storms, floods, and erosion have always been hazards, in combination with rising sea levels they now threaten approximately $1 trillion in national wealth held in coastal real estate and the continued viability of coastal communities that depend on coastal water, land, and other resources for economic health and cultural integrity (Ch. 15: Tribes, KM 1 and 2).

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/coastal.

Impacts of the 2017 Hurricane Season

Quintana Perez dumps water from a cooler into floodwaters in the aftermath of Hurricane Irma in Immokalee, Florida. *From Figure 8.6 (Photo credit: AP Photo/Gerald Herbert).*

9 Oceans and Marine Resources

Coral reefs in the U.S. Virgin Islands

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure. Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species. Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species. Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future, and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

Americans rely on ocean ecosystems for food, jobs, recreation, energy, and other vital services. Increased atmospheric carbon dioxide levels change ocean conditions through three main factors: warming seas, ocean acidification, and deoxygenation. These factors are transforming ocean ecosystems, and these transformations are already impacting the U.S. economy and coastal communities, cultures, and businesses.

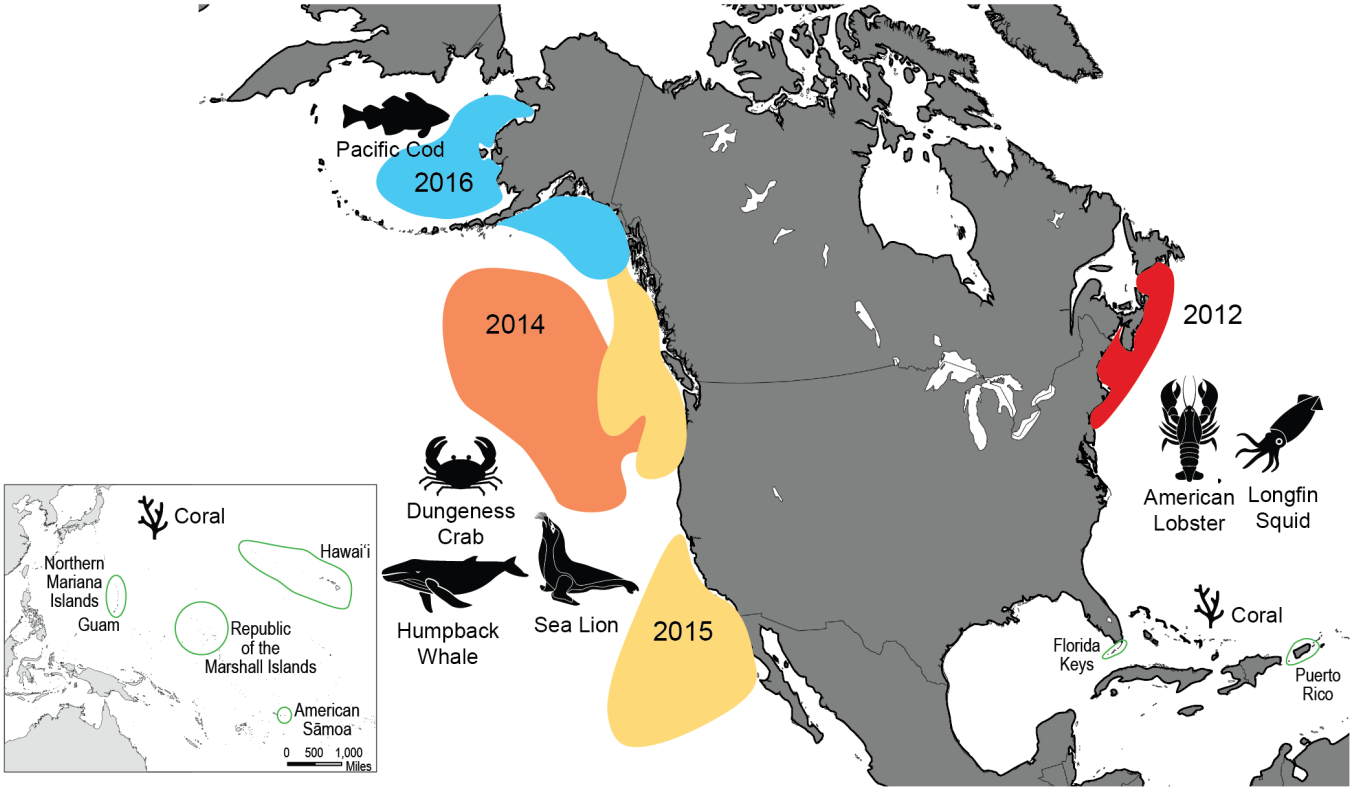
While climate-driven ecosystem changes are pervasive in the ocean, the most apparent impacts are occurring in tropical and polar ecosystems, where ocean warming is causing the loss of two vulnerable habitats: coral reef and sea ice ecosystems. The extent of sea ice in the Arctic is decreasing, which represents a direct loss of important habitat for animals like polar bears and ringed seals that use it for hunting, shelter, migration, and reproduction, causing their abundances to decline (Ch. 26: Alaska, KM 1). Warming has led to mass bleaching and/or outbreaks of coral diseases off the coastlines of Puerto Rico, the U.S. Virgin Islands, Florida, Hawai‘i, and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4) that threaten reef ecosystems and the people who depend on them. The loss of the recreational benefits alone from coral reefs in the United States is expected to reach $140 billion (discounted at 3% in 2015 dollars) by 2100. Reducing greenhouse gas emissions (for example, under RCP4.5); (see the Scenario Products section of Appendix 3 for more on scenarios) could reduce these cumulative losses by as much as $5.4 billion but will not avoid many ecological and economic impacts.

Ocean warming, acidification, and deoxygenation are leading to changes in productivity, recruitment, survivorship, and, in some cases, active movements of species to track their preferred temperature conditions, with most moving northward or into deeper water with warming oceans. These changes are impacting the distribution and availability of many commercially and recreationally valuable fish and invertebrates. The effects of ocean warming, acidification, and deoxygenation on marine species will interact with fishery management decisions, from seasonal and spatial closures to annual quota setting, allocations, and fish stock rebuilding plans. Accounting for these factors is the cornerstone of climate-ready fishery management. Even without directly accounting for climate effects, precautionary fishery management and better incentives can increase economic benefits and improve resilience.

Short-term changes in weather or ocean circulation can combine with long-term climate trends to produce periods of very unusual ocean conditions that can have significant impacts on coastal communities. Two such events have been particularly well documented: the 2012 marine heat wave in the northwestern Atlantic Ocean and the sequence of warm ocean events between 2014 and 2016 in the northeastern Pacific Ocean, including a large, persistent area of very warm water referred to as “the Blob.” Ecosystems within these regions experienced very warm conditions (more than 3.6°F [2°C] above the normal range) that persisted for several months or more. Extreme events in the oceans other than those related to temperature, including ocean acidification and low-oxygen events, can lead to significant disruptions to ecosystems and people, but they can also motivate preparedness and adaptation.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/oceans.

Extreme Events in U.S. Waters Since 2012



The 2012 North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event. The North Pacific event began in 2014 and extended toward the shore in 2015 and into the Gulf of Alaska in 2016, leading to a large bloom of toxic algae that impacted the Dungeness crab fishery and contributed directly and indirectly to deaths of sea lions and humpback whales. U.S. coral reefs that experienced moderate to severe bleaching during the 2015–2016 global mass bleaching event are indicated by coral icons. *From Figure 9.3 (Source: Gulf of Maine Research Institute).*

10 Agriculture and Rural Communities

Tyringham, Massachusetts

Key Message 1

Reduced Agricultural Productivity

Food and forage production will decline in regions experiencing increased frequency and duration of drought. Shifting precipitation patterns, when associated with high temperatures, will intensify wildfires that reduce forage on rangelands, accelerate the depletion of water supplies for irrigation, and expand the distribution and incidence of pests and diseases for crops and livestock. Modern breeding approaches and the use of novel genes from crop wild relatives are being employed to develop higher-yielding, stress-tolerant crops.

Key Message 2

Degradation of Soil and Water Resources

The degradation of critical soil and water resources will expand as extreme precipitation events increase across our agricultural landscape. Sustainable crop production is threatened by excessive runoff, leaching, and flooding, which results in soil erosion, degraded water quality in lakes and streams, and damage to rural community infrastructure. Management practices to restore soil structure and the hydrologic function of landscapes are essential for improving resilience to these challenges.

Key Message 3

Health Challenges to Rural Populations and Livestock

Challenges to human and livestock health are growing due to the increased frequency and intensity of high temperature extremes. Extreme heat conditions contribute to heat exhaustion, heatstroke, and heart attacks in humans. Heat stress in livestock results in large economic losses for producers. Expanded health services in rural areas, heat-tolerant livestock, and improved design of confined animal housing are all important advances to minimize these challenges.

Key Message 4

Vulnerability and Adaptive Capacity of Rural Communities

Residents in rural communities often have limited capacity to respond to climate change impacts, due to poverty and limitations in community resources. Communication, transportation, water, and sanitary infrastructure are vulnerable to disruption from climate stressors. Achieving social resilience to these challenges would require increases in local capacity to make adaptive improvements in shared community resources.

In 2015, U.S. agricultural producers contributed $136.7 billion to the economy and accounted for 2.6 million jobs. About half of the revenue comes from livestock production. Other agriculture-related sectors in the food supply chain contributed an additional $855 billion of gross domestic product and accounted for 21 million jobs.

In 2013, about 46 million people, or 15% of the U.S. population, lived in rural counties covering 72% of the Nation's land area. From 2010 to 2015, a historic number of rural counties experienced population declines, and recent demographic trends point to relatively slow employment and population growth in rural areas as well as high rates of poverty. Rural communities, where livelihoods are more tightly interconnected with agriculture, are particularly vulnerable to the agricultural volatility related to climate.

Climate change has the potential to adversely impact agricultural productivity at local, regional, and continental scales through alterations in rainfall patterns, more frequent occurrences of climate extremes (including high temperatures or drought), and altered patterns of pest pressure. Risks associated with climate change depend on the rate and severity of the change and the ability of producers to adapt to changes. These adaptations include altering what is produced, modifying the inputs used for production, adopting new technologies, and adjusting management strategies.

U.S. agricultural production relies heavily on the Nation's land, water, and other natural resources, and these resources are affected directly by agricultural practices and by climate. Climate change is expected to increase the frequency of extreme precipitation events in many regions in the United States. Because increased precipitation extremes elevate the risk of surface runoff, soil erosion, and the loss of soil carbon, additional protective measures are needed to safeguard the progress that has been made in reducing soil erosion and water quality degradation through the implementation of grassed waterways, cover crops, conservation tillage, and waterway protection strips.

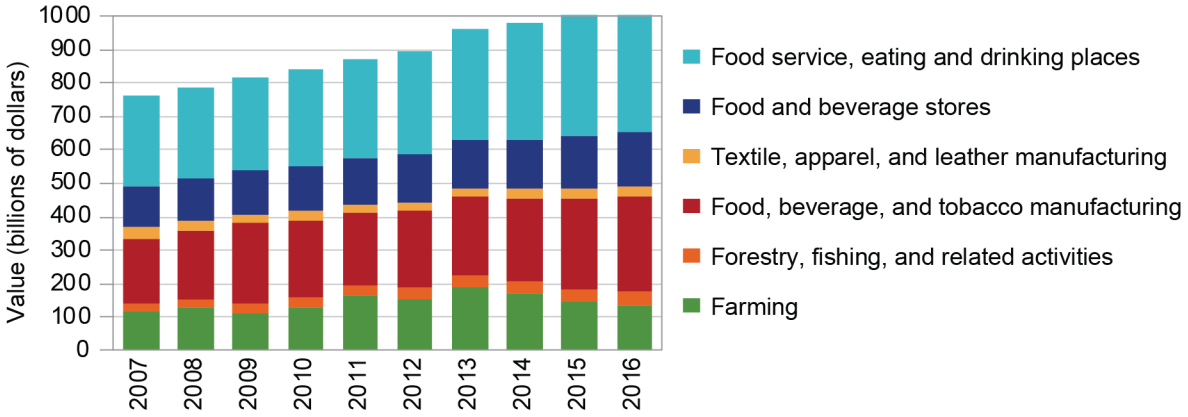
Climate change impacts, such as changes in extreme weather conditions, have a complex influence on human and livestock health. The consequences of climate change on the incidence of drought also impact the frequency and intensity of wildfires, and this holds implications for agriculture and rural communities. Rural populations are the stewards of most of the Nation's forests, watersheds, rangelands, agricultural land, and fisheries. Much of the rural economy is closely tied to the natural environment. Rural residents, and the lands they manage, have the potential to make important economic and conservation contributions to climate change

mitigation and adaptation, but their capacity to adapt is impacted by a host of demographic and economic concerns.

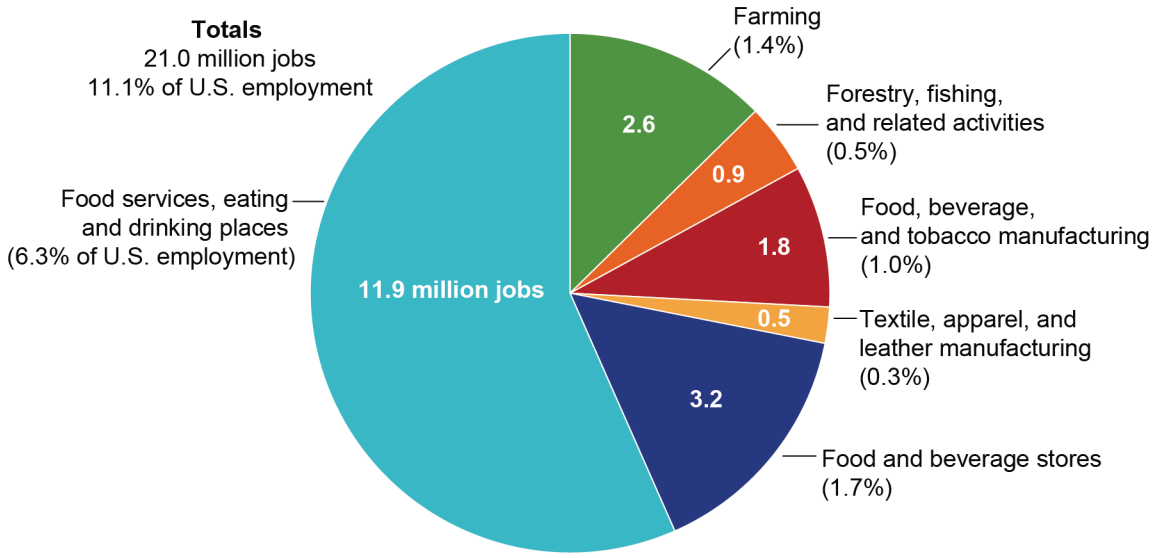
For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/agriculture-rural.

Agricultural Jobs and Revenue

(a) Value Added to GDP by Agriculture, Food, and Related Industries



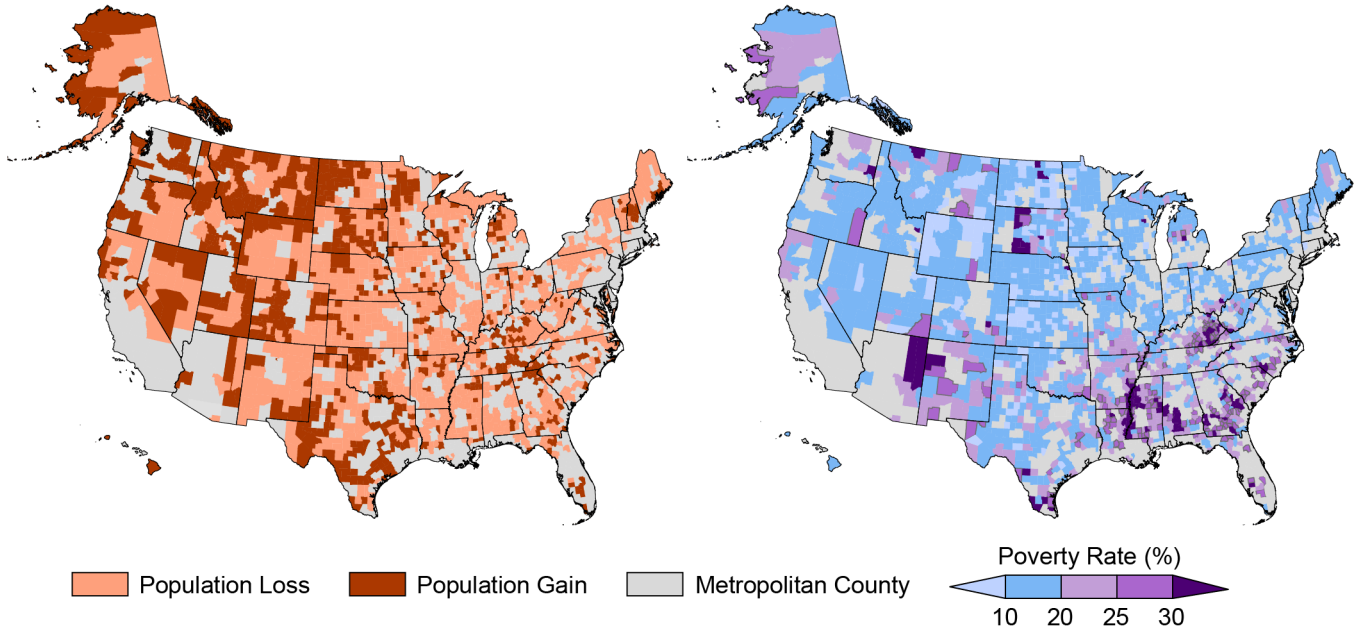
(b) Employment in Agriculture, Food, and Related Industries, 2015



The figure shows (a) the contribution of agriculture and related sectors to the U.S. economy and (b) employment figures in agriculture and related sectors (as of 2015). Agriculture and other food-related value-added sectors account for 21 million full- and part-time jobs and contribute about $1 trillion annually to the United States economy. *From Figure 10.1 (Source: adapted from Kassel et al. 2017).*

Population Changes and Poverty Rates in Rural Counties

(a) Nonmetro County Population Changes, 2010–2017 (b) Nonmetro County Poverty Rates, 2011–2015



The figure shows county-level (a) population changes for 2010–2017 and (b) poverty rates for 2011–2015 in rural U.S. communities. Rural populations are migrating to urban regions due to relatively slow employment growth and high rates of poverty. Data for the U.S. Caribbean region were not available at the time of publication of this report. *From Figure 10.2 (Sources: [a] adapted from ERS 2018; [b] redrawn from ERS 2017).*

11 Built Environment, Urban Systems, and Cities

Cleveland, Ohio

Key Message 1

Impacts on Urban Quality of Life

The opportunities and resources in urban areas are critically important to the health and well-being of people who work, live, and visit there. Climate change can exacerbate existing challenges to urban quality of life, including social inequality, aging and deteriorating infrastructure, and stressed ecosystems. Many cities are engaging in creative problem solving to improve quality of life while simultaneously addressing climate change impacts.

Key Message 2

Forward-Looking Design for Urban Infrastructure

Damages from extreme weather events demonstrate current urban infrastructure vulnerabilities. With its long service life, urban infrastructure must be able to endure a future climate that is different from the past. Forward-looking design informs investment in reliable infrastructure that can withstand ongoing and future climate risks.

Key Message 3

Impacts on Urban Goods and Services

Interdependent networks of infrastructure, ecosystems, and social systems provide essential urban goods and services. Damage to such networks from current weather extremes and future climate will adversely affect urban life. Coordinated local, state, and federal efforts can address these interconnected vulnerabilities.

Key Message 4

Urban Response to Climate Change

Cities across the United States are leading efforts to respond to climate change. Urban adaptation and mitigation actions can affect current and projected impacts of climate change and provide near-term benefits. Challenges to implementing these plans remain. Cities can build on local knowledge and risk management approaches, integrate social equity concerns, and join multicity networks to begin to address these challenges.

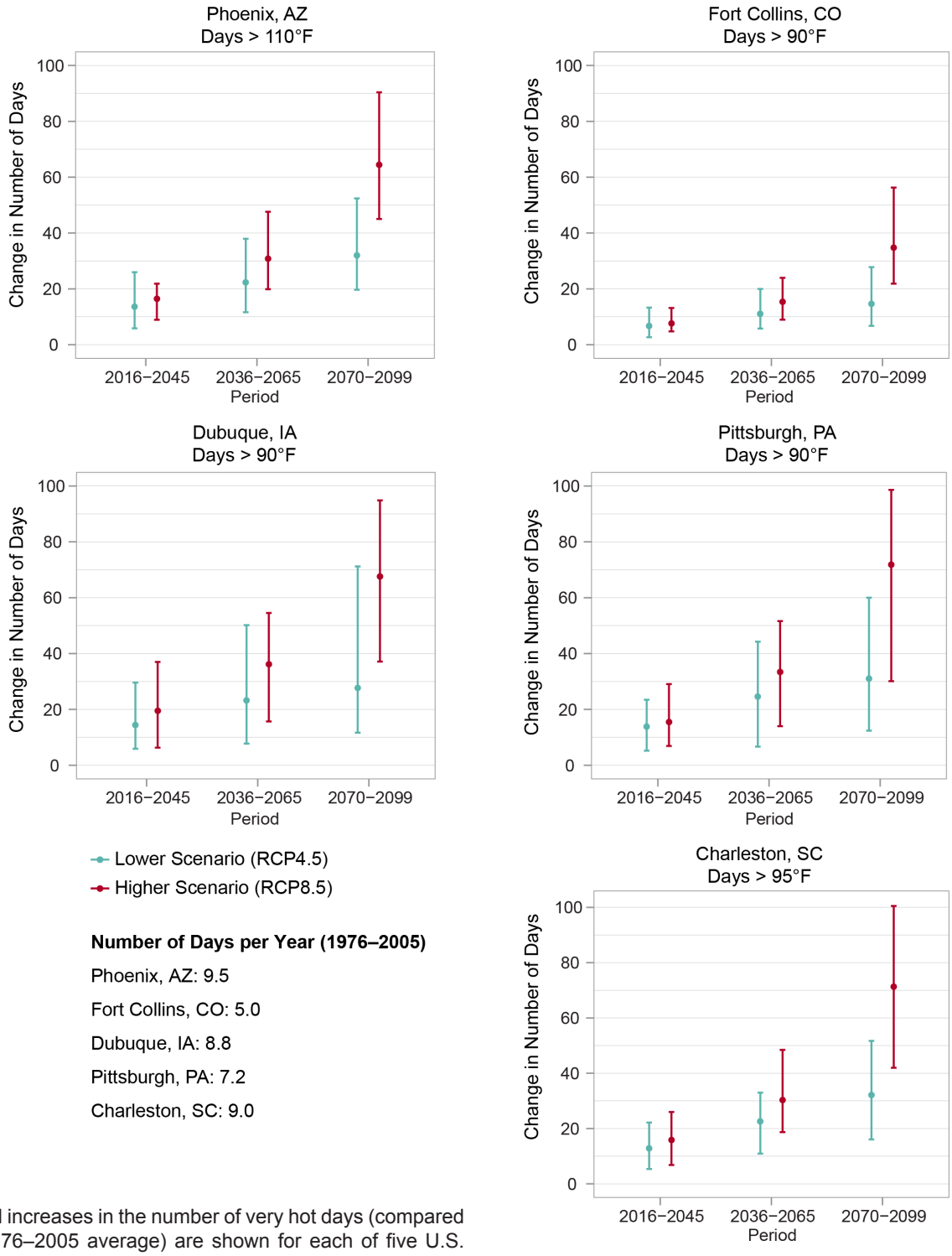
Urban areas, where the vast majority of Americans live, are engines of economic growth and contain land valued at trillions of dollars. Cities around the United States face a number of challenges to prosperity, such as social inequality, aging and deteriorating infrastructure, and stressed ecosystems. These social, infrastructure, and environmental challenges affect urban exposure and susceptibility to climate change effects.

Urban areas are already experiencing the effects of climate change. Cities differ across regions in the acute and chronic climate stressors they are exposed to and how these stressors interact with local geographic characteristics. Cities are already subject to higher surface temperatures because of the urban heat island effect, which is projected to get stronger. Recent extreme weather events reveal the vulnerability of the built environment (infrastructure such as residential and commercial buildings, transportation, communications, energy, water systems, parks, streets, and landscaping) and its importance to how people live, study, recreate, and work. Heat waves and heavy rainfalls are expected to increase in frequency and intensity. The way city residents respond to such incidents depends on their understanding of risk, their way of life, access to resources, and the communities to which they belong. Infrastructure designed for historical climate trends is vulnerable to future weather extremes and climate change. Investing in forward-looking design can help ensure that infrastructure performs acceptably under changing climate conditions.

Urban areas are linked to local, regional, and global systems. Situations where multiple climate stressors simultaneously affect multiple city sectors, either directly or through system connections, are expected to become more common. When climate stressors affect one sector, cascading effects on other sectors increase risks to residents' health and well-being. Cities across the Nation are taking action in response to climate change. U.S. cities are at the forefront of reducing greenhouse gas emissions and many have begun adaptation planning. These actions build urban resilience to climate change.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/built-environment.

Projected Change in the Number of Very Hot Days



Projected increases in the number of very hot days (compared to the 1976–2005 average) are shown for each of five U.S. cities under lower (RCP4.5) and higher (RCP8.5) scenarios. Here, very hot days are defined as those on which the daily high temperature exceeds a threshold value specific to each of the five U.S. cities shown. Dots represent the modeled median (50th percentile) values, and the vertical bars show the range of values (5th to 95th percentile) from the models used in the analysis. Modeled historical values are shown for the same temperature thresholds, for the period 1976–2005, in the lower left corner of the figure. These and other U.S. cities are projected to see an increase in the number of very hot days over the rest of this century under both scenarios, affecting people, infrastructure, green spaces, and the economy. Increased air conditioning and energy demands raise utility bills and can lead to power outages and blackouts. Hot days can degrade air and water quality, which in turn can harm human health and decrease quality of life. *From Figure 11.2 (Sources: NOAA NCEI, CICS-NC, and LMI)*.

12 Transportation

St. Louis, Missouri

Key Message 1

Transportation at Risk

A reliable, safe, and efficient U.S. transportation system is at risk from increases in heavy precipitation, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average temperature. Throughout this century, climate change will continue to pose a risk to U.S. transportation infrastructure, with regional differences.

Key Message 2

Impacts to Urban and Rural Transportation

Extreme events that increasingly impact the transportation network are inducing societal and economic consequences, some of which disproportionately affect vulnerable populations. In the absence of intervention, future changes in climate will lead to increasing transportation challenges, particularly because of system complexity, aging infrastructure, and dependency across sectors.

Key Message 3

Vulnerability Assessments

Engineers, planners, and researchers in the transportation field are showing increasing interest and sophistication in understanding the risks that climate hazards pose to transportation assets and services. Transportation practitioner efforts demonstrate the connection between advanced assessment and the implementation of adaptive measures, though many communities still face challenges and barriers to action.

Transportation is the backbone of economic activity, connecting manufacturers with supply chains, consumers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural landscapes. However, the ability of the transportation sector to perform reliably, safely, and efficiently is undermined by a changing climate. Heavy precipitation, coastal flooding, heat, wildfires, freeze–thaw cycles, and changes in average precipitation and temperature impact individual assets across all modes. These impacts threaten the performance of the entire network, with critical ramifications for economic vitality and mobility, particularly for vulnerable populations and urban infrastructure.

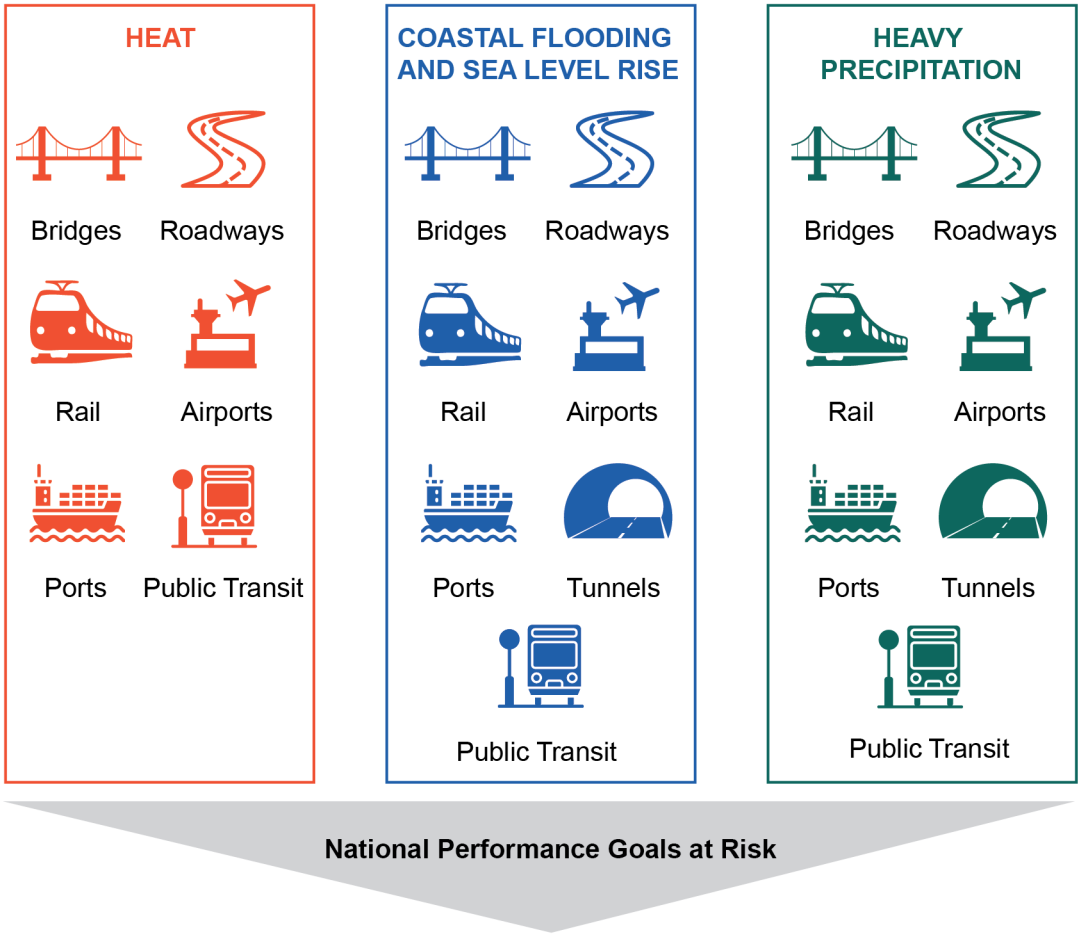
Sea level rise is progressively making coastal roads and bridges more vulnerable and less functional. Many coastal cities across the United States have already experienced an increase in high tide flooding that reduces the functionality of low-elevation roadways, rail, and bridges, often causing costly congestion and damage to infrastructure. Inland transportation infrastructure is highly vulnerable to intense rainfall and flooding. In some regions, the increasing frequency and intensity of heavy precipitation events reduce transportation system efficiency and increase accident risk. High temperatures can stress bridge integrity and have caused more frequent and extended delays to passenger and freight rail systems and air traffic.

Transportation is not only vulnerable to impacts of climate change but also contributes significantly to the causes of climate change. In 2016, the transportation sector became the top contributor to U.S. greenhouse gas emissions. The transportation system is rapidly growing and evolving in response to market demand and innovation. This growth could make climate mitigation and adaptation progressively more challenging to implement and more important to achieve. However, transportation practitioners are increasingly invested in addressing climate risks, as evidenced in more numerous and diverse assessments of transportation sector vulnerabilities across the United States.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/transportation.

U.S. Transportation Assets and Goals at Risk

Climate Change and Notable Vulnerabilities of Transportation Assets



Heavy precipitation, coastal flooding, heat, and changes in average precipitation and temperature affect assets (such as roads and bridges) across all modes of transportation. The figure shows major climate-related hazards and the transportation assets impacted. Photos illustrate national performance goals (listed in 23 U.S.C. § 150) that are at risk due to climate-related hazards. *From Figure 12.1 (Source: USGCRP. Photo credits from left to right: JAXPORT, Meredith Fordham Hughes [CC BY-NC 2.0]; Oregon Department of Transportation [CC BY 2.0]; NPS–Mississippi National River and Recreation Area; Flickr user Tom Driggers [CC BY 2.0]; Flickr user Mike Mozart [CC BY 2.0]; Flickr user Jeff Turner [CC BY 2.0]; Flickr user William Garrett [CC BY 2.0] — see https://creativecommons.org/licenses/ for specific Creative Commons licenses).*

13 Air Quality

Carr Fire, Shasta County, California, August 2018

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

Unless offset by additional emissions reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas, thereby worsening the detrimental health and environmental effects due to ozone. The climate penalty results from changes in local weather conditions, including temperature and atmospheric circulation patterns, as well as changes in ozone precursor emissions that are influenced by meteorology. Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions. The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.

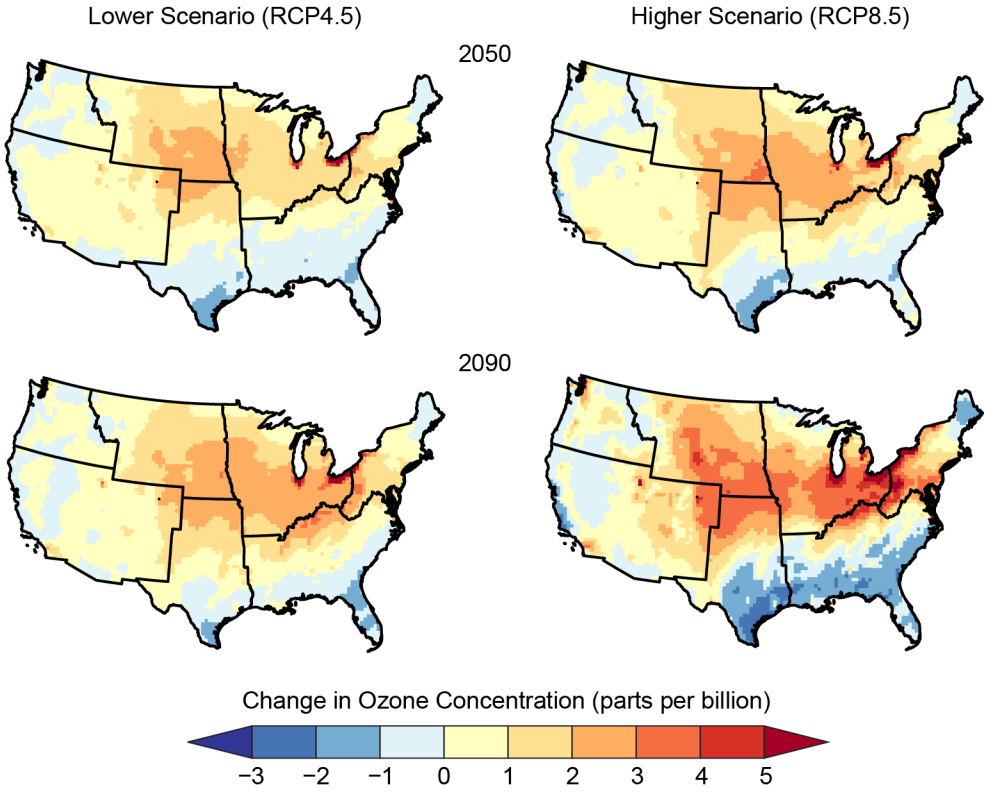
Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season and increased the frequency of large wildfires. Exposure to wildfire smoke increases the risk of respiratory disease, resulting in adverse impacts to human health. Longer fire seasons and increases in the number of large fires would impair both human health and visibility.

Climate change, specifically rising temperatures and increased carbon dioxide (CO_2) concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to the pollen.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions in the United States as well as 80% of emissions of nitrogen oxides (NO_x) and 96% of sulfur dioxide, the major precursor of sulfate aerosol. In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHG emissions can lower emissions of particulate matter (PM), ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/air-quality.

Projected Changes in Summer Season Ozone



The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai'i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. *From Figure 13.2 (Source: adapted from EPA 2017).*

14 Human Health

Algal bloom in Lake Erie in the summer of 2015

Key Message 1

Climate Change Affects the Health of All Americans

The health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being.

Key Message 2

Exposure and Resilience Vary Across Populations and Communities

People and communities are differentially exposed to hazards and disproportionately affected by climate-related health risks. Populations experiencing greater health risks include children, older adults, low-income communities, and some communities of color.

Key Message 3

Adaptation Reduces Risks and Improves Health

Proactive adaptation policies and programs reduce the risks and impacts from climate-sensitive health outcomes and from disruptions in healthcare services. Additional benefits to health arise from explicitly accounting for climate change risks in infrastructure planning and urban design.

Key Message 4

Reducing Greenhouse Gas Emissions Results in Health and Economic Benefits

Reducing greenhouse gas emissions would benefit the health of Americans in the near and long term. By the end of this century, thousands of American lives could be saved and hundreds of billions of dollars in health-related economic benefits gained each year under a pathway of lower greenhouse gas emissions.

Climate-related changes in weather patterns and associated changes in air, water, food, and the environment are affecting the health and well-being of the American people, causing injuries, illnesses, and death. Increasing temperatures, increases in the frequency and intensity of heat waves (since the 1960s), changes in precipitation patterns (especially increases in heavy precipitation), and sea level rise can affect our health through multiple pathways. Changes in weather and climate can degrade air and water quality; affect the geographic range, seasonality, and intensity of transmission of infectious diseases through food, water, and disease-carrying vectors (such as mosquitoes and ticks); and increase stresses that affect mental health and well-being.

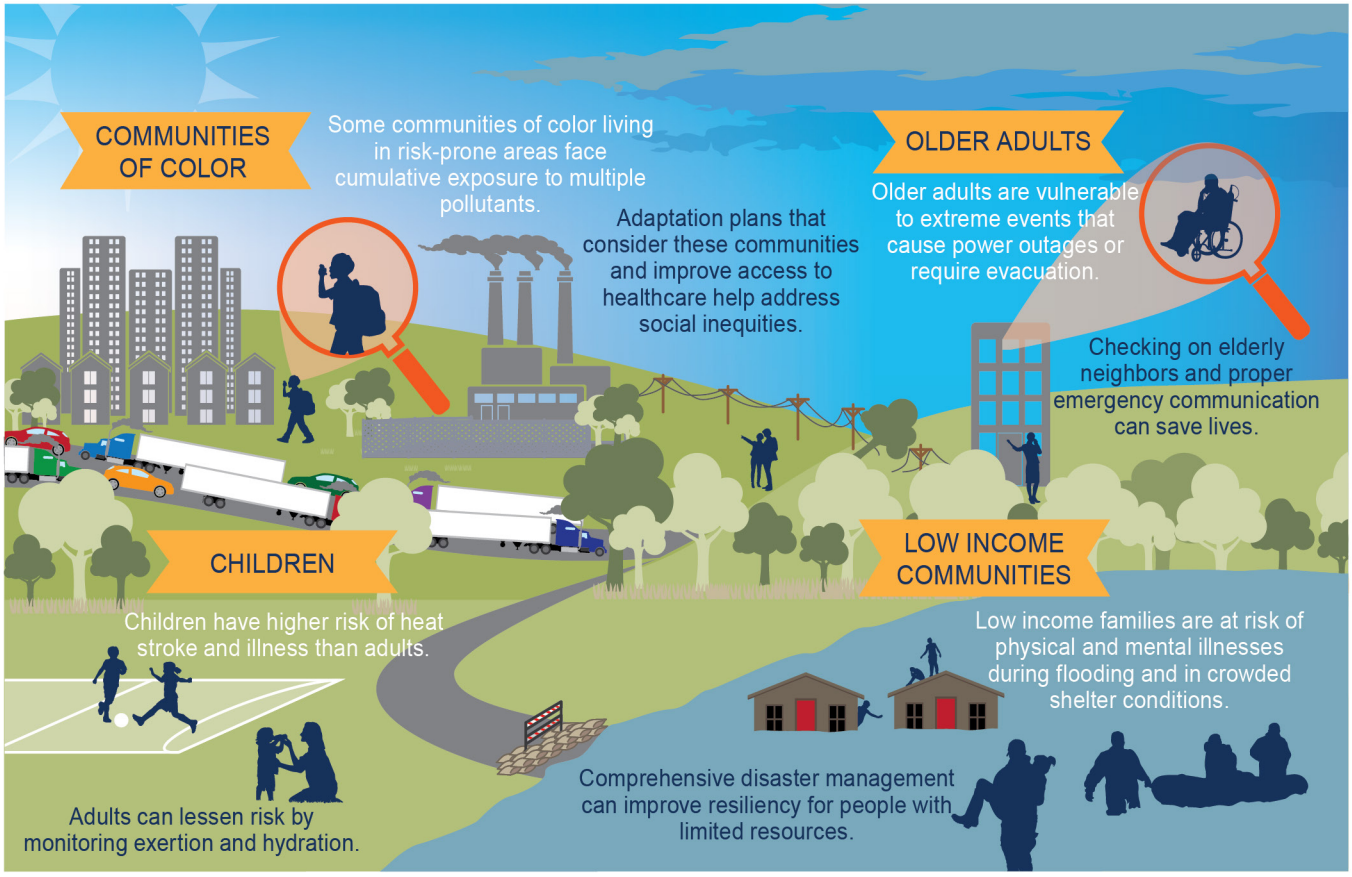
Changing weather patterns also interact with demographic and socioeconomic factors, as well as underlying health trends, to influence the extent of the consequences of climate change for individuals and communities. While all Americans are at risk of experiencing adverse climate-related health outcomes, some populations are disproportionately vulnerable.

The risks of climate change for human health are expected to increase in the future, with the extent of the resulting impacts dependent on the effectiveness of adaptation efforts and on the magnitude and pattern of future climate change. Individuals, communities, public health departments, health-related organizations and facilities, and others are taking action to reduce health vulnerability to current climate change and to increase resilience to the risks projected in coming decades.

The health benefits of reducing greenhouse gas emissions could result in economic benefits of hundreds of billions of dollars each year by the end of the century. Annual health impacts and health-related costs are projected to be approximately 50% lower under a lower scenario (RCP4.5) compared to a higher scenario (RCP8.5). These estimates would be even larger if they included the benefits of health outcomes that are difficult to quantify, such as avoided mental health impacts or long-term physical health impacts.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/health.

Vulnerable Populations



Examples of populations at higher risk of exposure to adverse climate-related health threats are shown along with adaptation measures that can help address disproportionate impacts. When considering the full range of threats from climate change as well as other environmental exposures, these groups are among the most exposed, most sensitive, and have the least individual and community resources to prepare for and respond to health threats. White text indicates the risks faced by those communities, while dark text indicates actions that can be taken to reduce those risks. *From Figure 14.2 (Source: EPA).*

15 Tribes and Indigenous Peoples

Wind River Indian Reservation students collect seeds for a land restoration project.

Key Message 1

Indigenous Livelihoods and Economies at Risk

Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises. Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure that will be impacted increasingly by changes in climate.

Key Message 2

Physical, Mental, and Indigenous Values-Based Health at Risk

Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate. As these changes continue, the health of individuals and communities will be uniquely challenged by climate impacts to lands, waters, foods, and other plant and animal species. These impacts threaten sites, practices, and relationships with cultural, spiritual, or ceremonial importance that are foundational to Indigenous peoples' cultural heritages, identities, and physical and mental health.

Key Message 3

Adaptation, Disaster Management, Displacement, and Community-Led Relocations

Many Indigenous peoples have been proactively identifying and addressing climate impacts; however, institutional barriers exist in the United States that severely limit their adaptive capacities. These barriers include limited access to traditional territory and resources and the limitations of existing policies, programs, and funding mechanisms in accounting for the unique conditions of Indigenous communities. Successful adaptation in Indigenous contexts relies on use of Indigenous knowledge, resilient and robust social systems and protocols, a commitment to principles of self-determination, and proactive efforts on the part of federal, state, and local governments to alleviate institutional barriers.

Indigenous peoples in the United States are diverse and distinct political and cultural groups and populations. Though they may be affected by climate change in ways that are similar to others in the United States, Indigenous peoples can also be affected uniquely and disproportionately. Many Indigenous peoples have lived in particular areas for hundreds if not thousands of years. Indigenous peoples' histories and shared experience engender distinct knowledge about climate change impacts and strategies for adaptation. Indigenous peoples' traditional knowledge systems can play a role in advancing understanding of climate change and in developing more comprehensive climate adaptation strategies.

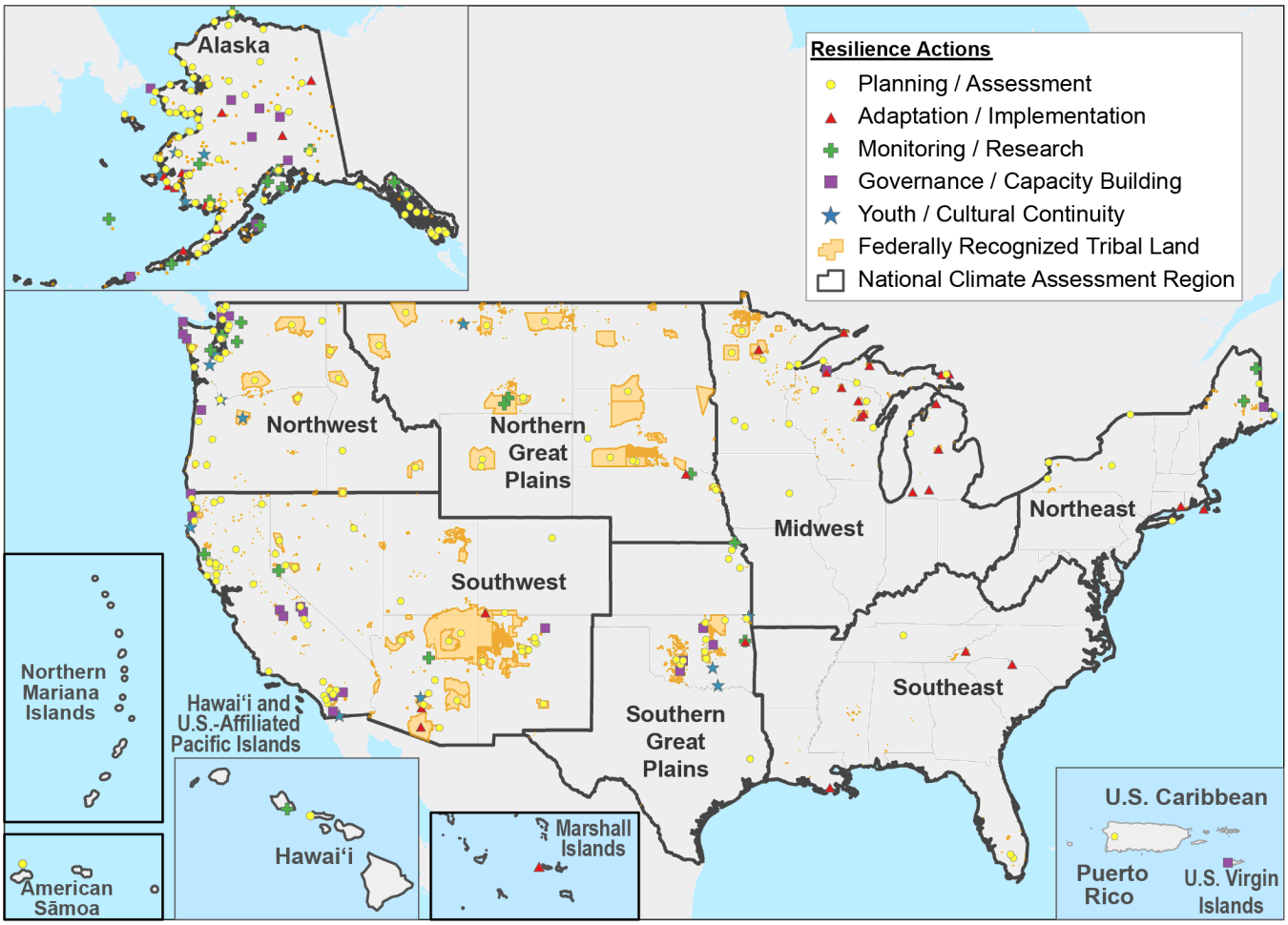
Observed and projected changes of increased wildfire, diminished snowpack, pervasive drought, flooding, ocean acidification, and sea level rise threaten the viability of Indigenous peoples' traditional subsistence and commercial activities that include agriculture, hunting and gathering, fisheries, forestry, energy, recreation, and tourism enterprises. Despite institutional barriers to tribal self-determination stemming from federal trust authority over tribal trust lands, a number of tribes have adaptation plans that include a focus on subsistence and commercial economic activities. Some tribes are also pursuing climate mitigation actions through the development of renewable energy on tribal lands.

Climate impacts to lands, waters, foods, and other plant and animal species threaten cultural heritage sites and practices that sustain intra- and intergenerational relationships built on sharing traditional knowledges, food, and ceremonial or cultural objects. This weakens place-based cultural identities, may worsen historical trauma still experienced by many Indigenous peoples in the United States, and adversely affects mental health and Indigenous values-based understandings of health.

Throughout the United States, climate-related disasters are causing Indigenous communities to consider or actively pursue relocation as an adaptation strategy. Challenges to Indigenous actions to address disaster management and recovery, displacement, and relocation in the face of climate change include economic, social, political, and legal considerations that severely constrain their abilities to respond to rapid ecological shifts and complicate action toward safe and self-determined futures for these communities.

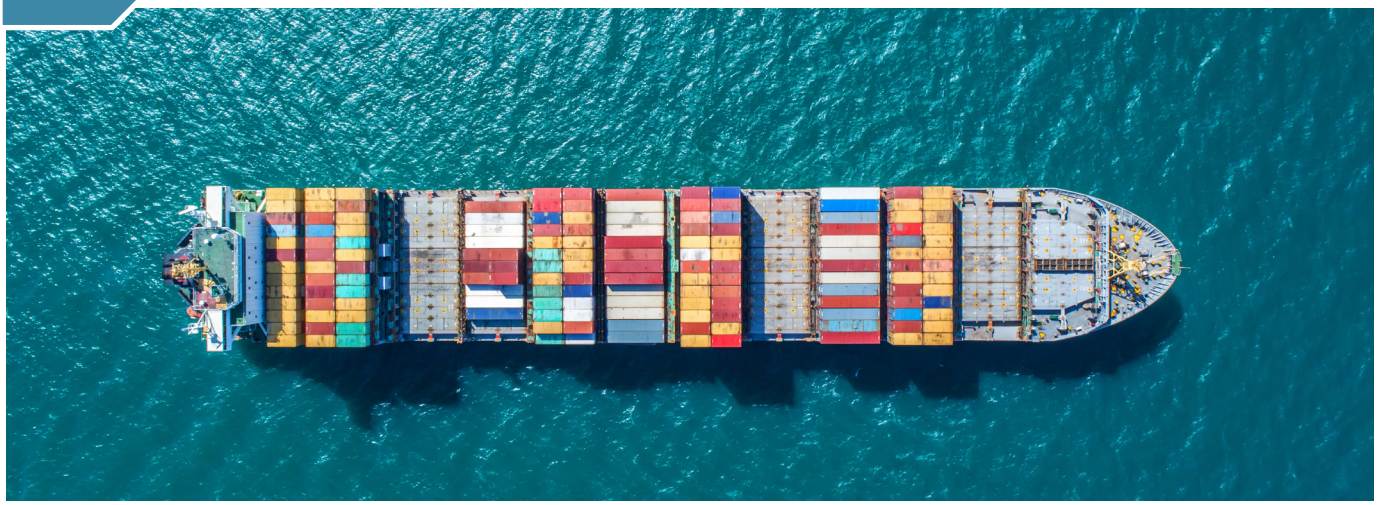
For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/tribes.

Indigenous Peoples' Climate Initiatives and Plans



Many Indigenous peoples are taking steps to adapt to climate change impacts. Search the online version of this map by activity type, region, and sector to find more information and links to each project: https://biamaps.doi.gov/nca/. To provide feedback and add new projects for inclusion in the database, see: https://www.bia.gov/bia/ots/tribal-resilience-program/nca/. Thus far, tribal entities in the Northwest have the highest concentration of climate activities (Ch. 24: Northwest). For other case studies of selected tribal adaptation activities, see both the Institute for Tribal Environmental Professionals' Tribal Profiles, and Tribal Case Studies within the U.S. Climate Resilience Toolkit. *From Figure 15.1 (Source: Bureau of Indian Affairs).*

16 Climate Effects on U.S. International Interests



Container ship bringing goods to port

Key Message 1

Economics and Trade

The impacts of climate change, variability, and extreme events outside the United States are affecting and are virtually certain to increasingly affect U.S. trade and economy, including import and export prices and businesses with overseas operations and supply chains.

Key Message 2

International Development and Humanitarian Assistance

The impacts of climate change, variability, and extreme events can slow or reverse social and economic progress in developing countries, thus undermining international aid and investments made by the United States and increasing the need for humanitarian assistance and disaster relief. The United States provides technical and financial support to help developing countries better anticipate and address the impacts of climate change, variability, and extreme events.

Key Message 3

Climate and National Security

Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning.

Key Message 4

Transboundary Resources

Shared resources along U.S. land and maritime borders provide direct benefits to Americans and are vulnerable to impacts from a changing climate, variability, and extremes. Multinational frameworks that manage shared resources are increasingly incorporating climate risk in their transboundary decision-making processes.

U.S. international interests, such as economics and trade, international development and humanitarian assistance, national security, and transboundary resources, are affected by impacts from climate change, variability, and extreme events. Long-term changes in climate could lead to large-scale shifts in the global availability and prices of a wide array of agricultural, energy, and other goods, with corresponding impacts on the U.S. economy. Some U.S.-led businesses are already working to reduce their exposure to risks posed by a changing climate.

U.S. investments in international development are sensitive to climate-related impacts and will likely be undermined by more frequent and intense extreme events, such as droughts, floods, and tropical cyclones. These events can impede development efforts and result in greater demand for U.S. humanitarian assistance and disaster relief. In response, the U.S. government has funded adaptation programs that seek to reduce vulnerability to climate impacts in critical sectors.

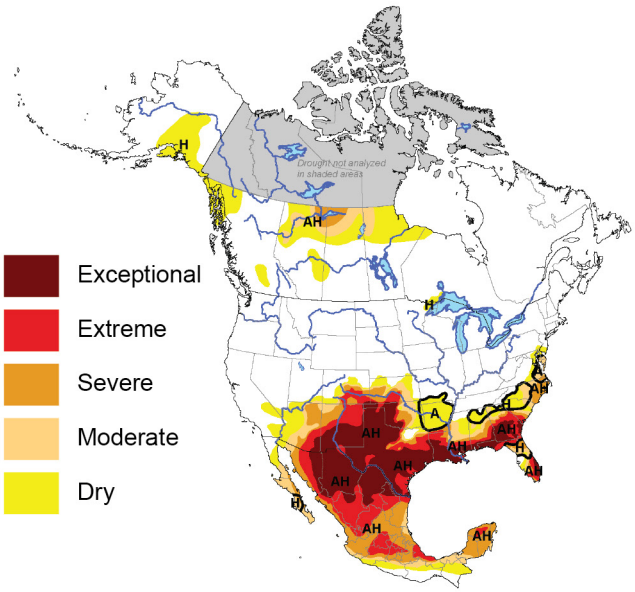
Climate change, variability, and extreme events increase risks to national security through direct impacts on U.S. military infrastructure and, more broadly, through the relationship between climate-related stress on societies and conflict. Direct linkages between climate and conflict are unclear, but climate variability has been shown to affect conflict through intermediate processes, including resource competition, commodity price shocks, and food insecurity. The U.S. military is working to fully understand these threats and to incorporate projected climate changes into long-term planning.

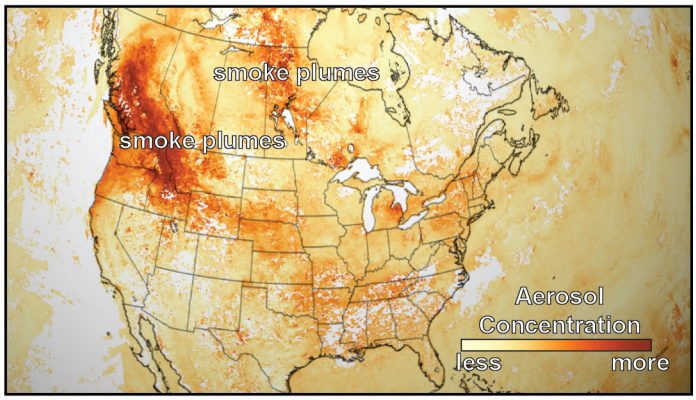
The impacts of changing weather and climate patterns across U.S. international borders affect those living in the United States. The changes pose new challenges for the management of shared and transboundary resources. Many bilateral agreements and public–private partnerships are incorporating climate risk and adaptive management into their near- and long-term strategies.

U.S. cooperation with international and other national scientific organizations improves access to global information and strategic partnerships, which better positions the Nation to observe, understand, assess, and respond to the impacts associated with climate change, variability, and extremes on national interests both within and outside of U.S. borders.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/international.

Transboundary Climate-Related Impacts





Shown here are examples of climate-related impacts spanning U.S. national borders. (left) The North American Drought Monitor map for June 2011 shows drought conditions along the U.S.–Mexico border. Darker colors indicate greater intensity of drought (the letters A and H indicate agricultural and hydrological drought, respectively). (right) Smoke from Canadian wildfires in 2017 was detected by satellite sensors built to detect aerosols in the atmosphere. The darker orange areas indicate higher concentrations of smoke and hazy conditions moving south from British Columbia to the United States. *From Figure 16.4 (Sources: [left] adapted from NOAA 2018, [right] adapted from NOAA 2018).*

17 Sector Interactions, Multiple Stressors, and Complex Systems

Landslide blocking a road in California

Key Message 1

Interactions Among Sectors

The sectors and systems exposed to climate (for example, energy, water, and agriculture) interact with and depend on one another and other systems less directly exposed to climate (such as the financial sector). In addition, these interacting systems are not only exposed to climate-related stressors such as floods, droughts, and heat waves, they are also subject to a range of non-climate factors, from population movements to economic fluctuations to urban expansion. These interactions can lead to complex behaviors and outcomes that are difficult to predict. It is not possible to fully understand the implications of climate change on the United States without considering the interactions among sectors and their consequences.

Key Message 2

Multisector Risk Assessment

Climate change risk assessment benefits from a multisector perspective, encompassing interactions among sectors and both climate and non-climate stressors. Because such interactions and their consequences can be challenging to identify in advance, effectively assessing multisector risks requires tools and approaches that integrate diverse evidence and that consider a wide range of possible outcomes.

Key Message 3

Management of Interacting Systems

The joint management of interacting systems can enhance the resilience of communities, industries, and ecosystems to climate-related stressors. For example, during drought events, river operations can be managed to balance water demand for drinking water, navigation, and electricity production. Such integrated approaches can help avoid missed opportunities or unanticipated tradeoffs associated with the implementation of management responses to climate-related stressors.

Key Message 4

Advancing Knowledge

Predicting the responses of complex, interdependent systems will depend on developing meaningful models of multiple, diverse systems, including human systems, and methods for characterizing uncertainty.

The world we live in is a web of natural, built, and social systems—from global and regional climate; to the electric grid; to water management systems such as dams, rivers, and canals; to managed and unmanaged forests; and to financial and economic systems. Climate affects many of these systems individually, but they also affect one another, and often in ways that are hard to predict. In addition, while climate-related risks such as heat waves, floods, and droughts have an important influence on these interconnected systems, these systems are also subject to a range of other factors, such as population growth, economic forces, technological change, and deteriorating infrastructure.

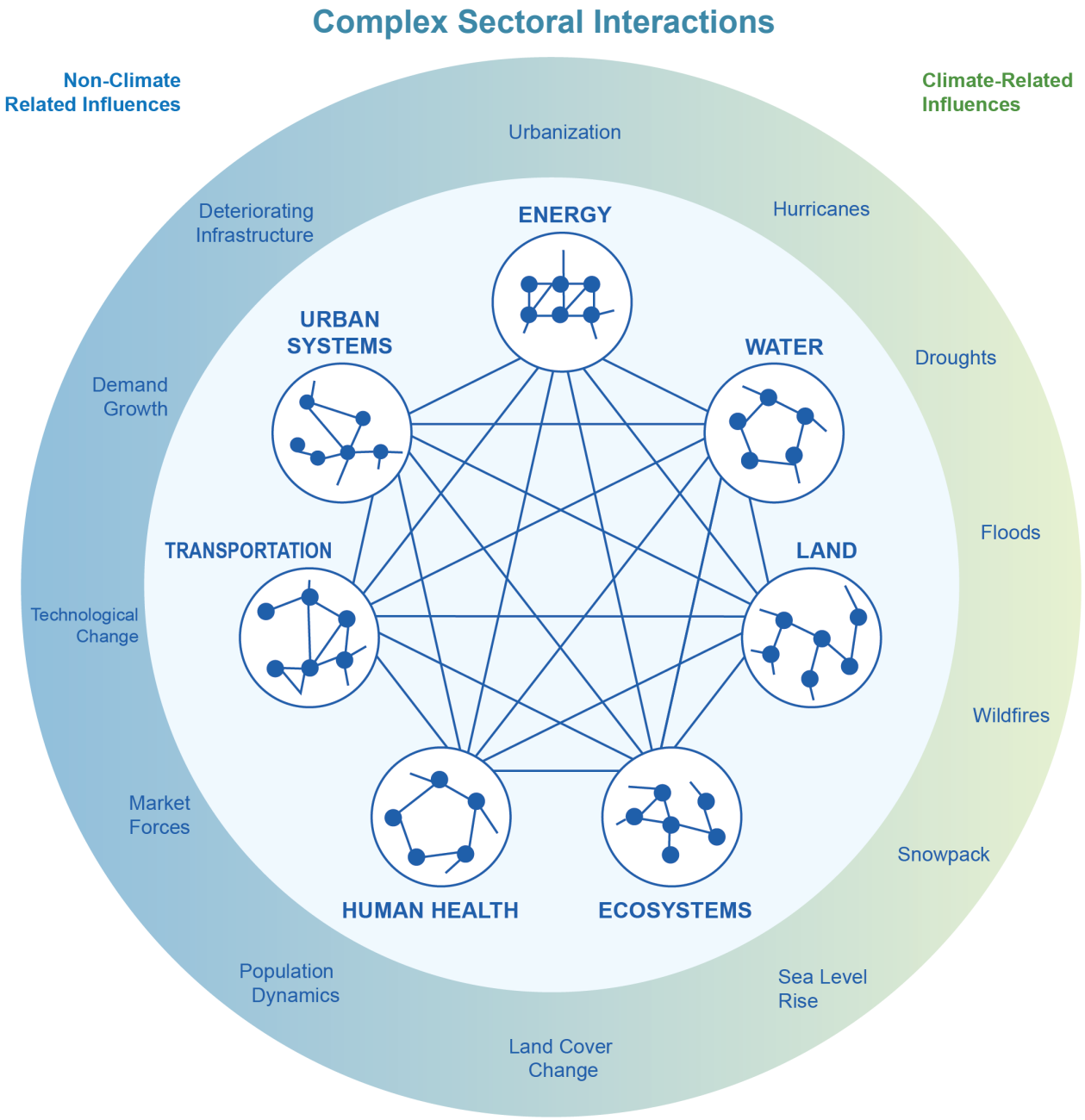
A key factor in assessing risk in this context is that it is hard to quantify and predict all the ways in which climate-related stressors might lead to severe or widespread consequences for natural, built, and social systems. A multisector perspective can help identify such critical risks ahead of time, but uncertainties will always remain regarding exactly how consequences will materialize in the future. Therefore, effectively assessing multisector risks requires different tools and approaches than would be applied to understand a single sector by itself.

In interacting systems, management responses within one system influence how other systems respond. Failure to anticipate interdependencies can lead to missed opportunities for managing the risks of climate change; it can also lead to management responses that increase risks to other parts of the system. Despite the challenge of managing system interactions, there are opportunities to learn from experience to guide future risk management decisions.

There is a large gap in the multisector and multiscale tools and frameworks that are available to describe how different human systems interact with one another and with the earth system, and how those interactions affect the total system response to the many stressors they are subject to, including climate-related stressors.

Characterizing the nature of such interactions and building the capacity to model them are important research challenges.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/complex-systems.



Sectors are interacting and interdependent through physical, social, institutional, environmental, and economic linkages. These sectors and the interactions among them are affected by a range of climate-related and non-climate influences. *From Figure 17.1 (Sources: Pacific Northwest National Laboratory, Arizona State University, and Cornell University).*

Banner Photo Credits

2. Climate: An atmospheric river pours moisture into the western United States in February 2017. *NASA Earth Observatory images by Jesse Allen and Joshua Stevens, using VIIRS data from the Suomi National Polar-orbiting Partnership and IMERG data provided courtesy of the Global Precipitation Mission (GPM) Science Team's Precipitation Processing System (PPS).*

3. Water: Levee repair along the San Joaquin River in California, February 2017. *U.S. Army Corps of Engineers, Sacramento District.*

4. Energy: Linemen working to restore power in Puerto Rico after Hurricane Maria in 2017. *© Jeff Miller/Western Area Power Administration/Flickr. CC BY 2.0,* https://creativecommons.org/licenses/by/2.0/legalcode.

5. Land Changes: Agricultural fields near the Ririe Reservoir in Bonneville, Idaho. *© Sam Beebe/Flickr. CC BY 2.0,* https://creativecommons.org/licenses/by/2.0/legalcode.

6. Forests: California's multiyear drought killed millions of trees in low-elevation forests. *Nathan Stephenson/U.S. Geological Survey.*

7. Ecosystems: Kodiak National Wildlife Refuge, Alaska. *Lisa Hupp/U.S. Fish and Wildlife Service.*

8. Coastal: Natural "green barriers" help protect this Florida coastline and infrastructure from severe storms and floods. *NOAA.*

9. Oceans: Coral reefs in the U.S. Virgin Islands. *NOAA Coral Reef Conservation Program.*

10. Ag & Rural: Tyringham, Massachusetts. *© DenisTangneyJr/E+/Getty Images.*

11. Urban: Cleveland, Ohio. *© Erik Drost/Flickr. CC BY 2.0,* https://creativecommons.org/licenses/by/2.0/legalcode.

12. Transportation: St. Louis, Missouri. *© Cathy Morrison/Missouri Department of Transportation. CC BY-NC-SA 2.0,* https://creativecommons.org/licenses/by-nc-sa/2.0/legalcode.

13. Air Quality: Carr Fire, Shasta County, California, August 2018. *Sgt. Lani O. Pascual/U.S. Army National Guard.*

14. Human Health: Algal bloom in Lake Erie in summer 2015. *NOAA Great Lakes Environmental Research Laboratory.*

15. Tribes: Wind River Indian Reservation students collect seeds for a land restoration project. *U.S. Department of the Interior/Bureau of Land Management Wyoming.*

16: International: Container ship bringing goods to port. *© wissanu01/iStock/Getty Images.*

17. Complex Systems: Landslide blocking a road in California. *© gece33/E+/Getty Images.*

Note: Photos have been cropped from their original size in order to fit the report template.

Regions

Executive Summaries

18 Northeast

Bartram Bridge in Pennsylvania

Key Message 1

Changing Seasons Affect Rural Ecosystems, Environments, and Economies

The seasonality of the Northeast is central to the region's sense of place and is an important driver of rural economies. Less distinct seasons with milder winter and earlier spring conditions are already altering ecosystems and environments in ways that adversely impact tourism, farming, and forestry. The region's rural industries and livelihoods are at risk from further changes to forests, wildlife, snowpack, and streamflow.

Key Message 2

Changing Coastal and Ocean Habitats, Ecosystem Services, and Livelihoods

The Northeast's coast and ocean support commerce, tourism, and recreation that are important to the region's economy and way of life. Warmer ocean temperatures, sea level rise, and ocean acidification threaten these services. The adaptive capacity of marine ecosystems and coastal communities will influence ecological and socioeconomic outcomes as climate risks increase.

Key Message 3

Maintaining Urban Areas and Communities and Their Interconnectedness

The Northeast's urban centers and their interconnections are regional and national hubs for cultural and economic activity. Major negative impacts on critical infrastructure, urban economies, and nationally significant historic sites are already occurring and will become more common with a changing climate.

Key Message 4

Threats to Human Health

Changing climate threatens the health and well-being of people in the Northeast through more extreme weather, warmer temperatures, degradation of air and water quality, and sea level rise. These environmental changes are expected to lead to health-related impacts and costs, including additional deaths, emergency room visits and hospitalizations, and a lower quality of life. Health impacts are expected to vary by location, age, current health, and other characteristics of individuals and communities.

Key Message 5

Adaptation to Climate Change Is Underway

Communities in the Northeast are proactively planning and implementing actions to reduce risks posed by climate change. Using decision support tools to develop and apply adaptation strategies informs both the value of adopting solutions and the remaining challenges. Experience since the last assessment provides a foundation to advance future adaptation efforts.

The distinct seasonality of the Northeast's climate supports a diverse natural landscape adapted to the extremes of cold, snowy winters and warm to hot, humid summers. This natural landscape provides the economic and cultural foundation for many rural communities, which are largely supported by a diverse range of agricultural, tourism, and natural resource-dependent industries (see Ch. 10: Ag & Rural, Key Message 4). The recent dominant trend in precipitation throughout the Northeast has been towards increases in rainfall intensity, with increases in intensity exceeding those in other regions of the contiguous United States. Further increases in rainfall intensity are expected, with increases in total precipitation expected during the winter and spring but with little change in the summer. Monthly precipitation in the Northeast is projected to be about 1 inch greater for December through April by end of century (2070–2100) under the higher scenario (RCP8.5).

Ocean and coastal ecosystems are being affected by large changes in a variety of climate-related environmental conditions. These ecosystems support fishing and aquaculture, tourism and recreation, and coastal communities. Observed and projected increases in temperature, acidification, storm frequency and intensity, and sea levels are of particular concern for coastal and ocean ecosystems, as well as local communities and their interconnected social and economic systems. Increasing temperatures and changing seasonality on the Northeast Continental Shelf have affected marine organisms and the ecosystem in various ways. The warming trend experienced in the Northeast Continental Shelf has been associated with many fish and invertebrate species moving northward and to greater depths. Because of the diversity of the Northeast's coastal landscape, the impacts from storms and sea level rise will vary at different locations along the coast.

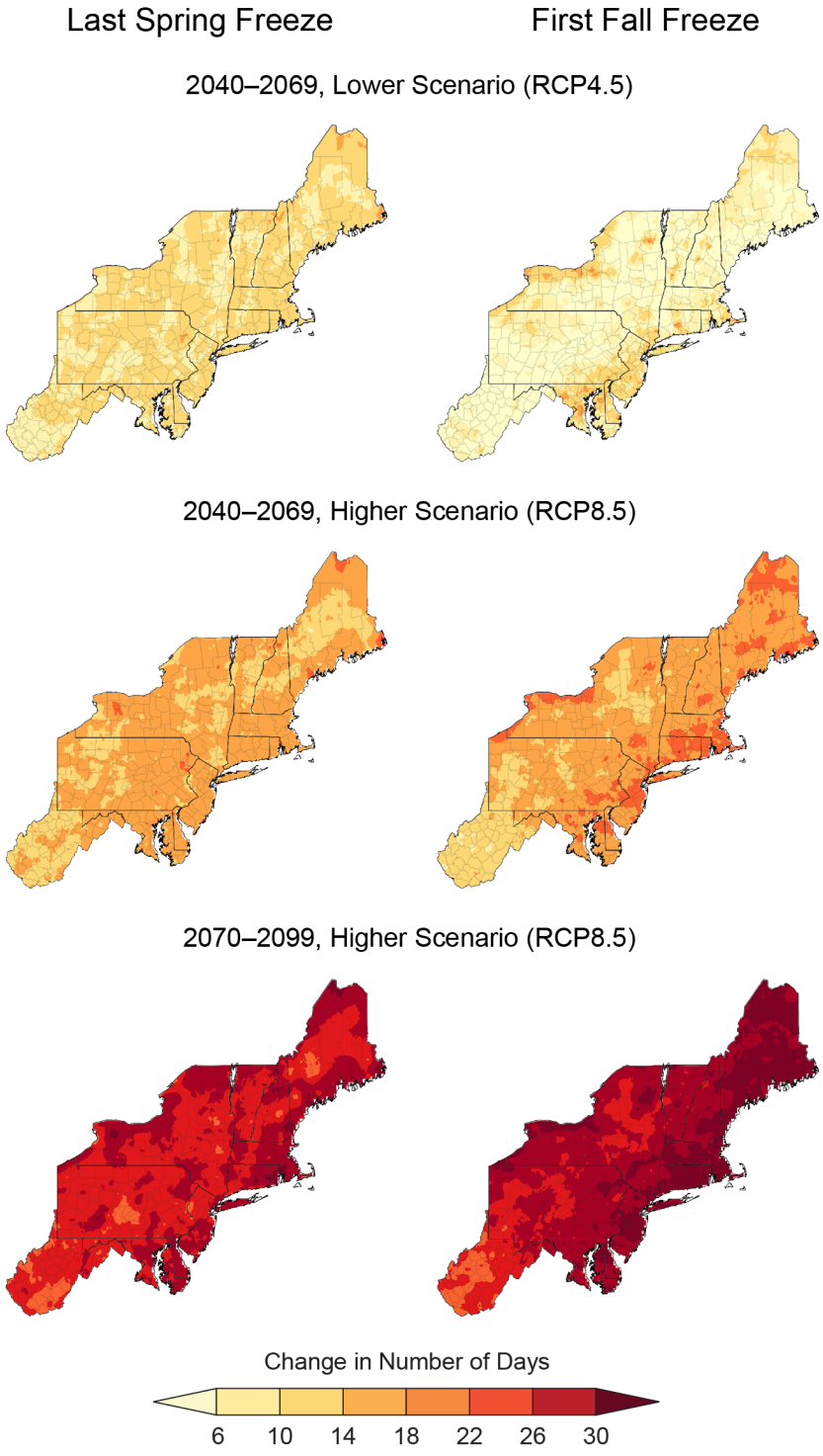
Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions due to the urban heat island effect. During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher than surrounding regions, leading to higher risk of heat-related death. Urban areas are at risk for large numbers of evacuated and displaced populations and damaged infrastructure due to both extreme precipitation events and recurrent flooding, potentially requiring significant emergency response efforts and consideration of a long-term commitment to rebuilding and adaptation, and/or support for relocation where needed. Much of the infrastructure in the Northeast, including drainage and sewer systems, flood and storm protection assets, transportation systems, and power supply, is nearing the end of its planned life expectancy. Climate-related disruptions will only exacerbate existing issues with aging infrastructure. Sea level rise has amplified storm impacts in the Northeast (Key Message 2), contributing to higher surges that extend farther inland, as demonstrated in New York City in the aftermath of Superstorm Sandy in 2012. Service and resource supply infrastructure in the Northeast is at increasing risk of disruption, resulting in lower quality of life, economic declines, and increased social inequality. Loss of public services affects the capacity of communities to function as administrative and economic centers and triggers disruptions of interconnected supply chains (Ch. 16: International, Key Message 1).

Increases in annual average temperatures across the Northeast range from less than 1°F (0.6°C) in West Virginia to about 3°F (1.7°C) or more in New England since 1901. Although the relative risk of death on very hot days is lower today than it was a few decades ago, heat-related illness and death remain significant public health problems in the Northeast. For example, a study in New York City estimated that in 2013 there were 133 excess deaths due to extreme heat. These projected increases in temperature are expected to lead to substantially more premature deaths, hospital admissions, and emergency department visits across the Northeast. For example, in the Northeast we can expect approximately 650 additional premature deaths per year from extreme heat by the year 2050 under either a lower (RCP4.5) or higher (RCP8.5) scenario and from 960 (under RCP4.5) to 2,300 (under RCP8.5) more premature deaths per year by 2090.

Communities, towns, cities, counties, states, and tribes across the Northeast are engaged in efforts to build resilience to environmental challenges and adapt to a changing climate. Developing and implementing climate adaptation strategies in daily practice often occur in collaboration with state and federal agencies. Advances in rural towns, cities, and suburban areas include low-cost adjustments of existing building codes and standards. In coastal areas, partnerships among local communities and federal and state agencies leverage federal adaptation tools and decision support frameworks. Increasingly, cities and towns across the Northeast are developing or implementing plans for adaptation and resilience in the face of changing climate. The approaches are designed to maintain and enhance the everyday lives of residents and promote economic development. In some cities, adaptation planning has been used to respond to present and future challenges in the built environment. Regional efforts have recommended changes in design standards when building, replacing, or retrofitting infrastructure to account for a changing climate.

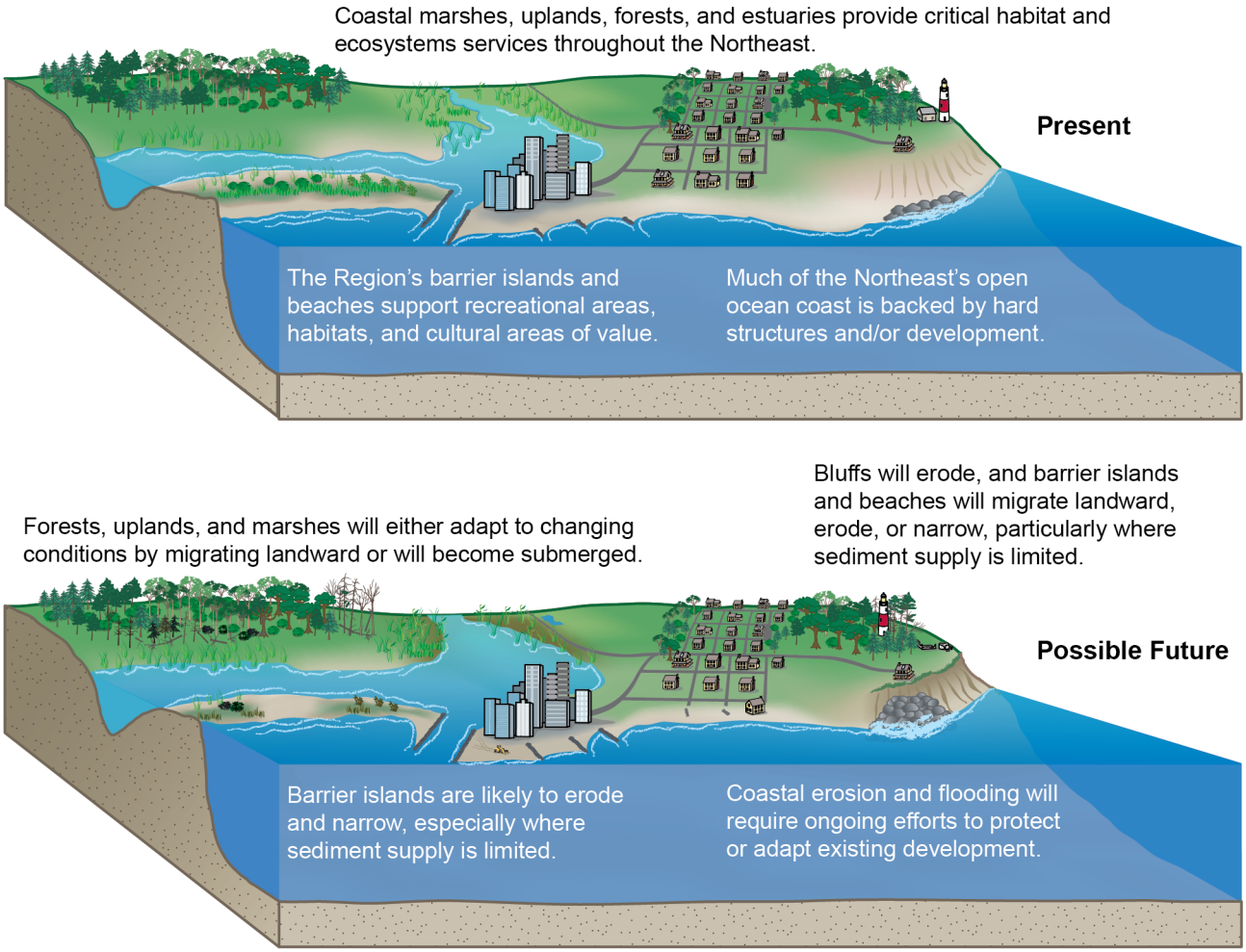
For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/northeast.

Lengthening of the Freeze-Free Period



These maps show projected shifts in the date of the last spring freeze (left column) and the date of the first fall freeze (right column) for the middle of the century (as compared to 1979–2008) under the lower scenario (RCP4.5; top row) and the higher scenario (RCP8.5; middle row). The bottom row shows the shift in these dates for the end of the century under the higher scenario. By the middle of the century, the freeze-free period across much of the Northeast is expected to lengthen by as much as two weeks under the lower scenario and by two to three weeks under the higher scenario. By the end of the century, the freeze-free period is expected to increase by at least three weeks over most of the region. *From Figure 18.3 (Source: adapted from Wolfe et al. 2018).*

Coastal Impacts of Climate Change



(top) The northeastern coastal landscape is composed of uplands and forested areas, wetlands and estuarine systems, mainland and barrier beaches, bluffs, headlands, and rocky shores, as well as developed areas, all of which provide a variety of important services to people and species. (bottom) Future impacts from intense storm activity and sea level rise will vary across the landscape, requiring a variety of adaptation strategies if people, habitats, traditions, and livelihoods are to be protected. *From Figure 18.7 (Source: U.S. Geological Survey)*.

19 Southeast

Red mangrove in Titusville, Florida

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health. The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change. Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems. As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today.

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors. By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts. Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence. Reduction of existing stresses can increase resilience.

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. These beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. While some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerous high temperatures, humidity, and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available to them, and economic situations.

Observed warming since the mid-20th century has been uneven in the Southeast region, with average daily minimum temperatures increasing three times faster than average daily maximum temperatures. The number of extreme rainfall events is increasing. Climate model simulations of future conditions project increases in both temperature and extreme precipitation.

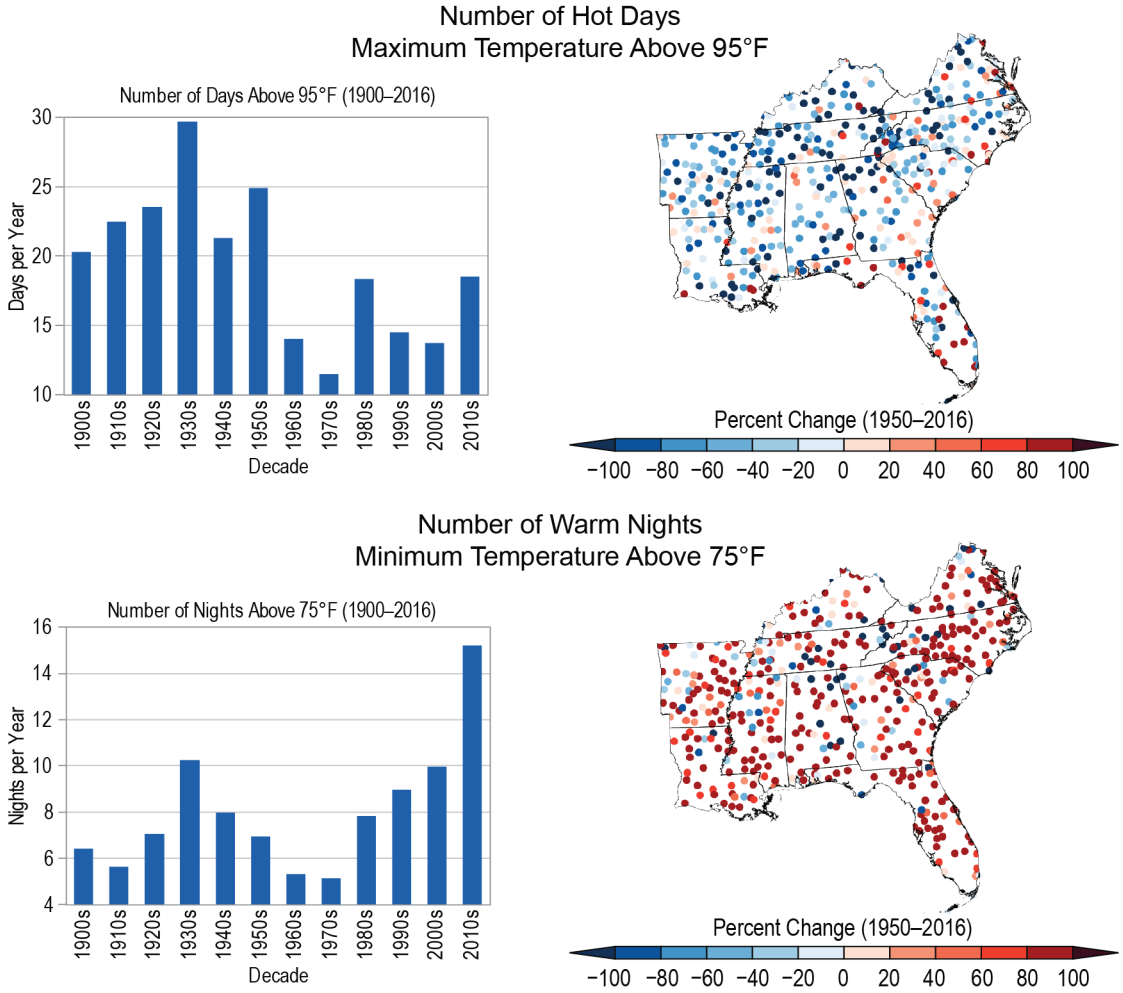
Trends towards a more urbanized and denser Southeast are expected to continue, creating new climate vulnerabilities. Cities across the Southeast are experiencing more and longer summer heat waves. Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors, and the major urban centers in the Southeast are already impacted by poor air quality during warmer months. Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, which will likely have cascading effects across the region. Infrastructure related to drinking water and wastewater treatment also has the potential to be compromised by climate-related events. Increases in extreme rainfall events and high tide coastal floods due to future climate change will impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Sea level rise is contributing to increased coastal flooding in the Southeast, and high tide flooding already poses daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the region. There have been numerous instances of intense rainfall events that have had devastating impacts on inland communities in recent years.

The ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change. Sea level rise will result in the rapid conversion of coastal, terrestrial, and freshwater ecosystems to tidal saline habitats. Reductions in the frequency and intensity of cold winter temperature extremes are already allowing tropical and subtropical species to move northward and replace more temperate species. Warmer winter temperatures are also expected to facilitate the northward movement of problematic invasive species, which could transform natural systems north of their current distribution. In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire practices.

Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate changes. Climate trends and possible climate futures show patterns that are already impacting—and are projected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity. Future temperature increases are projected to pose challenges to human health. Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems. Rural communities tend to be more vulnerable to these changes due to factors such as demography, occupations, earnings, literacy, and poverty incidence. In fact, a recent economic study using a higher scenario (RCP8.5) suggests that the southern and midwestern populations are likely to suffer the largest losses from future climate changes in the United States. Climate change tends to compound existing vulnerabilities and exacerbate existing inequities. Already poor regions, including those found in the Southeast, are expected to continue incurring greater losses than elsewhere in the United States.

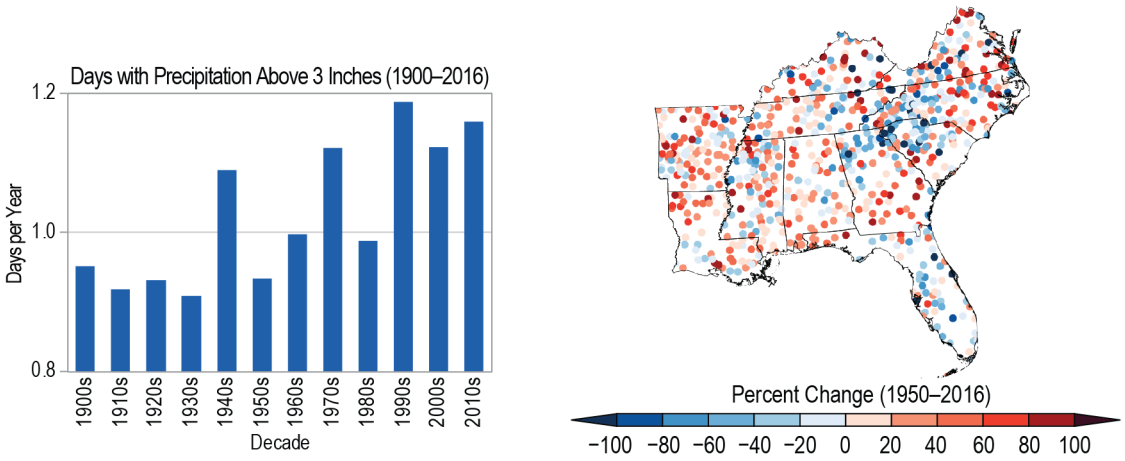
For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/southeast.

Historical Changes in Hot Days and Warm Nights



Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country. Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. *From Figure 19.1 (Sources: NOAA NCEI and CICS-NC)*.

Historical Change in Heavy Precipitation



The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The number of days with heavy precipitation has increased at most stations, particularly since the 1980s. *From Figure 19.3 (Sources: NOAA NCEI and CICS-NC).*

20 U.S. Caribbean

San Juan, Puerto Rico

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, the Caribbean climate is changing and is projected to be increasingly variable as levels of greenhouse gases in the atmosphere increase.

The high percentage of coastal area relative to the total island land area in the U.S. Caribbean means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. High levels of exposure and sensitivity to risk in the U.S. Caribbean region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas. The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands (USVI) have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets; service-related industries account for more than 60% of the USVI economy. Beaches, affected by sea level rise and erosion, are among the main tourist attractions. In Puerto Rico, critical infrastructure (for example, drinking water pipelines and pump stations, sanitary pipelines and pump stations, wastewater treatment plants, and power plants) is vulnerable to the effects of sea level rise, storm surge, and flooding. In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

Climate change will likely result in water shortages due to an overall decrease in annual rainfall, a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean. These shortages would result from some locations within the Caribbean experiencing longer dry seasons and shorter, but wetter, wet seasons in the future. Extended dry seasons are projected to increase fire likelihood. Excessive rainfall, coupled with poor construction practices, unpaved roads, and steep slopes, can exacerbate erosion rates and have adverse effects on reservoir capacity, water quality, and nearshore marine habitats.

Ocean warming poses a significant threat to the survival of corals and will likely also cause shifts in associated habitats that compose the coral reef ecosystem. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean acidification also is likely to diminish the structural integrity of coral habitats. Studies show that major shifts in fisheries distribution and changes to the structure and composition of marine habitats adversely affect food security, shoreline protection, and economies throughout the Caribbean.

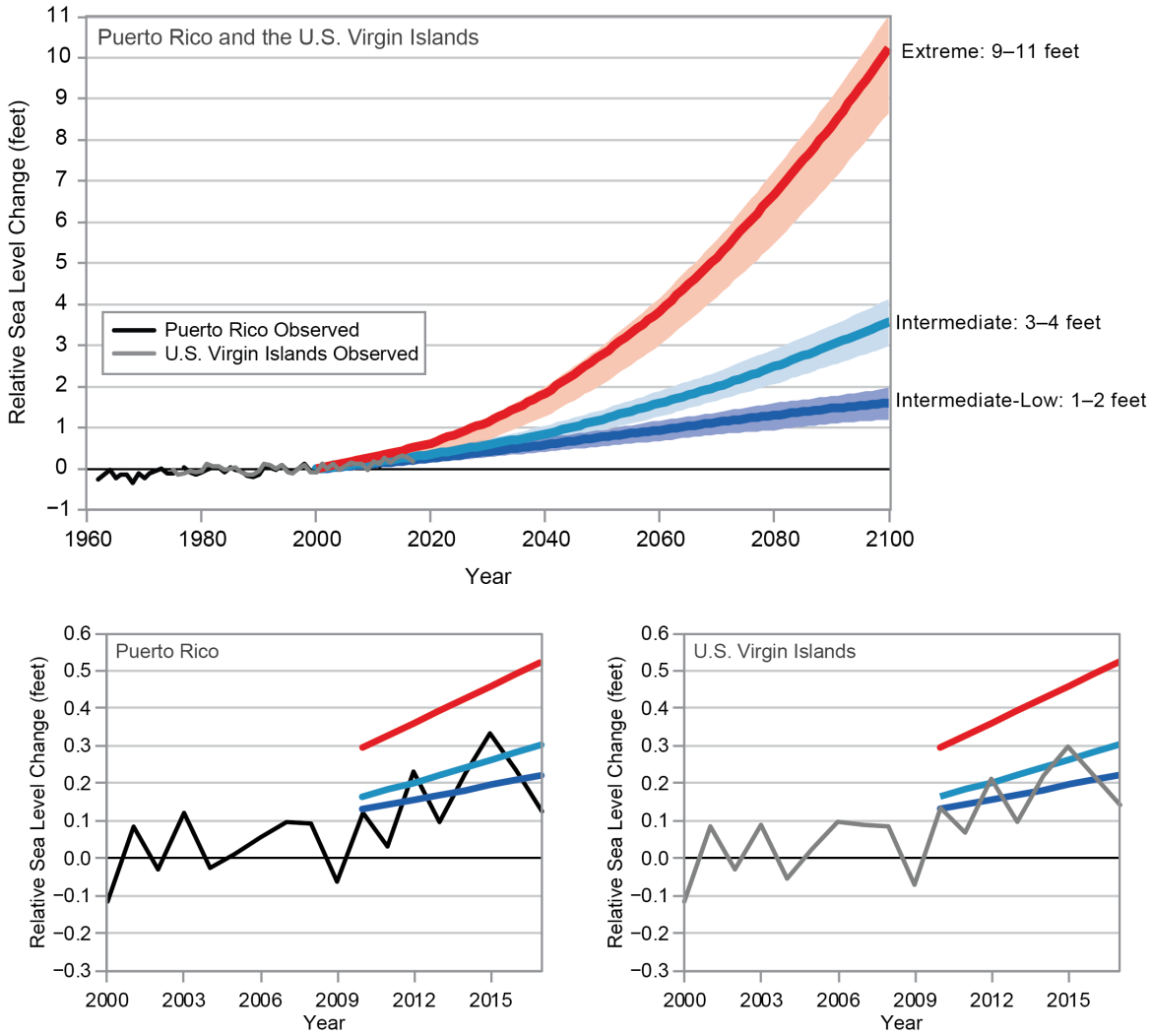
In Puerto Rico, the annual number of days with temperatures above 90°F has increased over the last four and a half decades. During that period, stroke and cardiovascular disease, which are influenced by such elevated temperatures, became the primary causes of death. Increases in

average temperature and in extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region. Many farmers in the tropics, including the U.S. Caribbean, are considered small-holding, limited resource farmers and often lack the resources and/or capital to adapt to changing conditions.

Most Caribbean countries and territories share the need to assess risks, enable actions across scales, and assess changes in ecosystems to inform decision-making on habitat protection under a changing climate. U.S. Caribbean islands have the potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction.

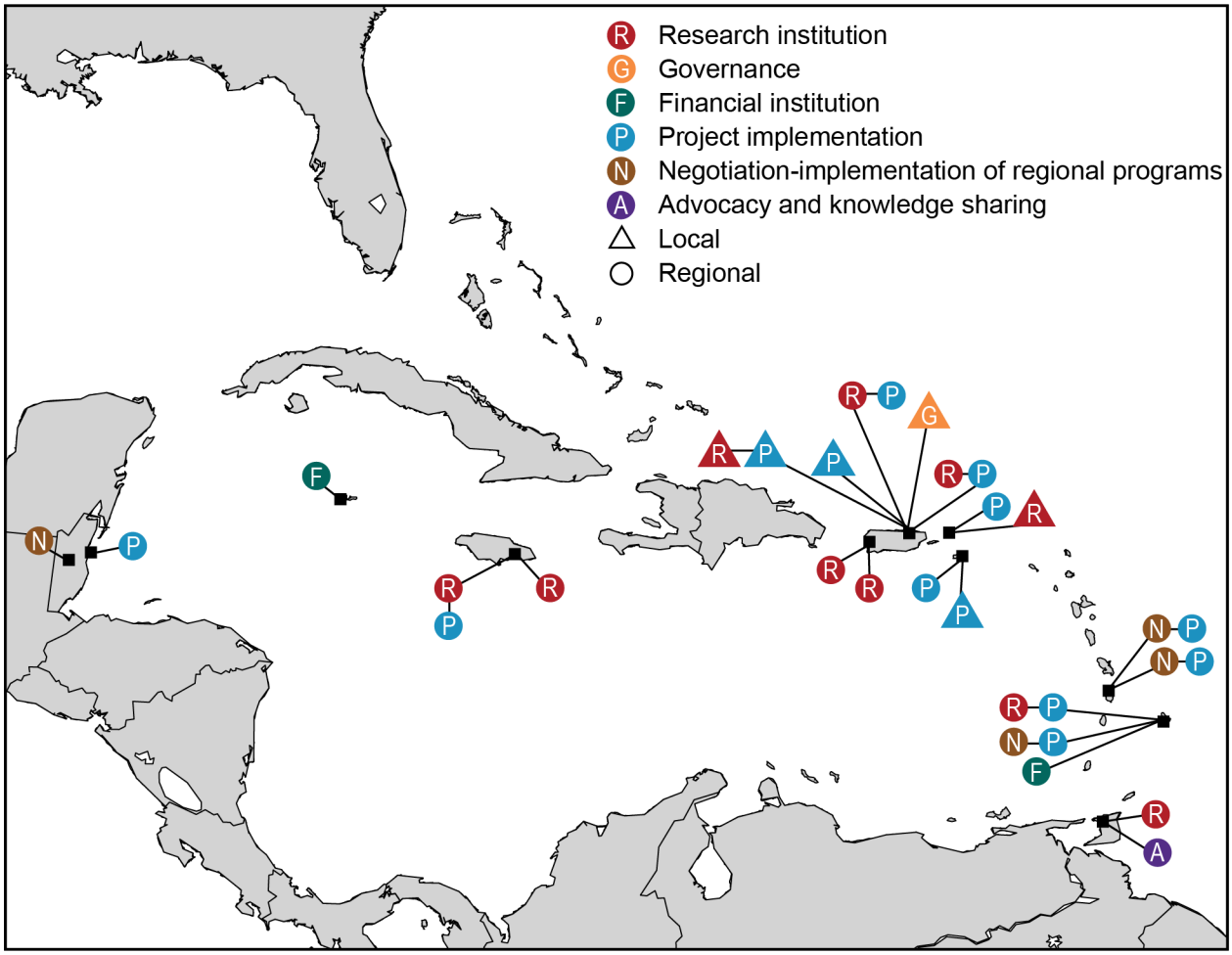
For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/caribbean.

Observed and Projected Sea Level Rise



(top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. *From Figure 20.6 (Sources: NOAA NCEI and CICS-NC).*

Climate Risk Management Organizations



Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. *From Figure 20.18 (Sources: NOAA and the USDA Caribbean Climate Hub)*.

21 Midwest

Carson, Wisconsin

Key Message 1

Agriculture

The Midwest is a major producer of a wide range of food and animal feed for national consumption and international trade. Increases in warm-season absolute humidity and precipitation have eroded soils, created favorable conditions for pests and pathogens, and degraded the quality of stored grain. Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances.

Key Message 2

Forestry

Midwest forests provide numerous economic and ecological benefits, yet threats from a changing climate are interacting with existing stressors such as invasive species and pests to increase tree mortality and reduce forest productivity. Without adaptive actions, these interactions will result in the loss of economically and culturally important tree species such as paper birch and black ash and are expected to lead to the conversion of some forests to other forest types or even to non-forested ecosystems by the end of the century. Land managers are beginning to manage risk in forests by increasing diversity and selecting for tree species adapted to a range of projected conditions.

Key Message 3

Biodiversity and Ecosystems

The ecosystems of the Midwest support a diverse array of native species and provide people with essential services such as water purification, flood control, resource provision, crop pollination, and recreational opportunities. Species and ecosystems, including the important freshwater resources of the Great Lakes, are typically most at risk when climate stressors, like temperature increases, interact with land-use change, habitat loss, pollution, nutrient inputs, and nonnative invasive species. Restoration of natural systems, increases in the use of green infrastructure, and targeted conservation efforts, especially of wetland systems, can help protect people and nature from climate change impacts.

Key Message 4

Human Health

Climate change is expected to worsen existing health conditions and introduce new health threats by increasing the frequency and intensity of poor air quality days, extreme high temperature events, and heavy rainfalls; extending pollen seasons; and modifying the distribution of disease-carrying pests and insects. By mid-century, the region is projected to experience substantial, yet avoidable, loss of life, worsened health conditions, and economic impacts estimated in the billions of dollars as a result of these changes. Improved basic health services and increased public health measures—including surveillance and monitoring—can prevent or reduce these impacts.

Key Message 5

Transportation and Infrastructure

Storm water management systems, transportation networks, and other critical infrastructure are already experiencing impacts from changing precipitation patterns and elevated flood risks. Green infrastructure is reducing some of the negative impacts by using plants and open space to absorb storm water. The annual cost of adapting urban storm water systems to more frequent and severe storms is projected to exceed $500 million for the Midwest by the end of the century.

Key Message 6

Community Vulnerability and Adaptation

At-risk communities in the Midwest are becoming more vulnerable to climate change impacts such as flooding, drought, and increases in urban heat islands. Tribal nations are especially vulnerable because of their reliance on threatened natural resources for their cultural, subsistence, and economic needs. Integrating climate adaptation into planning processes offers an opportunity to better manage climate risks now. Developing knowledge for decision-making in cooperation with vulnerable communities and tribal nations will help to build adaptive capacity and increase resilience.

The Midwest is home to over 60 million people, and its active economy represents 18% of the U.S. gross domestic product. The region is probably best known for agricultural production. Increases in growing-season temperature in the Midwest are projected to be the largest contributing factor to declines in the productivity of U.S. agriculture. Increases in humidity in spring through mid-century are expected to increase rainfall, which will increase the potential for soil erosion and further reduce planting-season workdays due to waterlogged soil.

Forests are a defining characteristic of many landscapes within the Midwest, covering more than 91 million acres. However, a changing climate, including an increased frequency of late-growing-season drought conditions, is worsening the effects of invasive species, insect pests, and plant disease as trees experience periodic moisture stress. Impacts from human activities, such as logging, fire suppression, and agricultural expansion, have lowered the diversity of the Midwest's forests from the pre-Euro-American settlement period. Natural resource managers are taking steps to address these issues by increasing the diversity of trees and introducing species suitable for a changing climate.

The Great Lakes play a central role in the Midwest and provide an abundant freshwater resource for water supplies, industry, shipping, fishing, and recreation, as well as a rich and diverse ecosystem. These important ecosystems are under stress from pollution, nutrient and sediment inputs from agricultural systems, and invasive species. Lake surface temperatures are increasing, lake ice cover is declining, the seasonal stratification of temperatures in the lakes is occurring earlier in the year, and summer evaporation rates are increasing. Increasing storm impacts and declines in coastal water quality can put coastal communities at risk. While several coastal communities have expressed willingness to integrate climate action into planning efforts, access to useful climate information and limited human and financial resources constrain municipal action.

Land conversion, and a wide range of other stressors, has already greatly reduced biodiversity in many of the region's prairies, wetlands, forests, and freshwater systems. Species are already responding to changes that have occurred over the last several decades, and rapid climate change over the next century is expected to cause or further amplify stress in many species and ecological systems in the

Midwest. The loss of species and the degradation of ecosystems have the potential to reduce or eliminate essential ecological services such as flood control, water purification, and crop pollination, thus reducing the potential for society to successfully adapt to ongoing changes. However, understanding these relationships also highlights important climate adaptation strategies. For example, restoring systems like wetlands and forested floodplains and implementing agricultural best management strategies that increase vegetative cover (cover crops and riparian buffers) can help reduce flooding risks and protect water quality.

Midwestern populations are already experiencing adverse health impacts from climate change, and these impacts are expected to worsen in the future. In the absence of mitigation, ground-level ozone concentrations are projected to increase across most of the Midwest, resulting in an additional 200–550 premature deaths in the region per year by 2050. Exposure to high temperatures impacts workers' health, safety, and productivity. Currently, days over 100°F in Chicago are rare. However, they could become increasingly more common by late century in both the lower and higher scenarios (RCP4.5 and RCP8.5).

The Midwest also has vibrant manufacturing, retail, recreation/tourism, and service sectors. The region's highways, railroads, airports, and navigable rivers are major modes for commerce activity. Increasing precipitation, especially heavy rain events, has increased the overall flood risk, causing disruption to transportation and damage to property and infrastructure. Increasing use of green infrastructure (including nature-based approaches, such as wetland restoration, and innovations like permeable pavements) and better engineering practices are beginning to address these issues.

Conservation Practices Reduce Impact of Heavy Rains
Integrating strips of native prairie vegetation into row crops has been shown to reduce sediment and nutrient loss from fields, as well as improve biodiversity and the delivery of ecosystem services. Iowa State University's STRIPS program is actively conducting research into this agricultural conservation practice. The inset shows a close-up example of a prairie vegetation strip. *From Figure 21.2 (Photo credits: [main photo] Lynn Betts, [inset] Farnaz Kordbacheh).*

Citizens and stakeholders value their health and the well-being of their communities—all of which are at risk from increased flooding, increased heat, and lower air and water quality under a changing climate. To better prevent and respond to these impacts, scholars and practitioners highlight the need to engage in risk-driven approaches that not only focus on assessing vulnerabilities but also include effective planning and implementation of adaptation options.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/midwest.

Forest Diversity Can Increase Resilience to Climate Change
The photo shows Menominee Tribal Enterprises staff creating opportunity from adversity by replanting a forest opening caused by oak wilt disease with a diverse array of tree and understory plant species that are expected to fare better under future climate conditions. *From Figure 21.4 (Photo credit: Kristen Schmitt).*

22 Northern Great Plains

Cattle grazing in the plains of western Montana

Key Message 1

Water

Water is the lifeblood of the Northern Great Plains, and effective water management is critical to the region's people, crops and livestock, ecosystems, and energy industry. Even small changes in annual precipitation can have large effects downstream; when coupled with the variability from extreme events, these changes make managing these resources a challenge. Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges.

Key Message 2

Agriculture

Agriculture is an integral component of the economy, the history, and the culture of the Northern Great Plains. Recently, agriculture has benefited from longer growing seasons and other recent climatic changes. Some additional production and conservation benefits are expected in the next two to three decades as land managers employ innovative adaptation strategies, but rising temperatures and changes in extreme weather events are very likely to have negative impacts on parts of the region. Adaptation to extremes and to longer-term, persistent climate changes will likely require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.

Key Message 3

Recreation and Tourism

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are at risk in a changing climate. Rising temperatures have already resulted in shorter snow seasons, lower summer streamflows, and higher stream temperatures and have negatively affected high-elevation ecosystems and riparian areas, with important consequences for local economies that depend on winter or river-based recreational activities. Climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational amenities they support. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, such as scenario planning, transboundary collaboration, and development of market-based tools.

Key Message 4

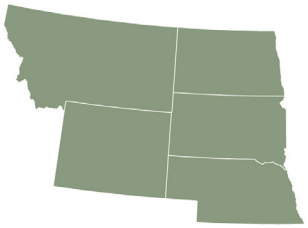
Energy

Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains. Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy as a whole. The energy sector is also a significant source of greenhouse gases and volatile organic compounds that contribute to climate change and ground-level ozone pollution.

Key Message 5

Indigenous Peoples

Indigenous peoples of the Northern Great Plains are at high risk from a variety of climate change impacts, especially those resulting from hydrological changes, including changes in snowpack, seasonality and timing of precipitation events, and extreme flooding and droughts as well as melting glaciers and reduction in streamflows. These changes are already resulting in harmful impacts to tribal economies, livelihoods, and sacred waters and plants used for ceremonies, medicine, and subsistence. At the same time, many tribes have been very proactive in adaptation and strategic climate change planning.



In the Northern Great Plains, the timing and quantity of both precipitation and runoff have important consequences for water supplies, agricultural activities, and energy production. Overall, climate projections suggest that the number of heavy precipitation events (events with greater than 1 inch per day of rainfall) is projected to increase. Moving forward, the magnitude of year-to-year variability overshadows the small projected average decrease in streamflow. Changes in extreme events are likely to overwhelm average changes in both the eastern and western regions of the Northern Great Plains. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

The Northern Great Plains region plays a critical role in national food security. Among other anticipated changes, projected warmer and generally wetter conditions with elevated atmospheric carbon dioxide concentrations are expected to increase the abundance and competitive ability of weeds and invasive species, increase livestock production and efficiency of production, and result in longer growing seasons at mid- and high latitudes. Net primary productivity, including crop yields and forage production, is also likely to increase, although an increasing number of extreme temperature events during critical pollination and grain fill periods is likely to reduce crop yields.

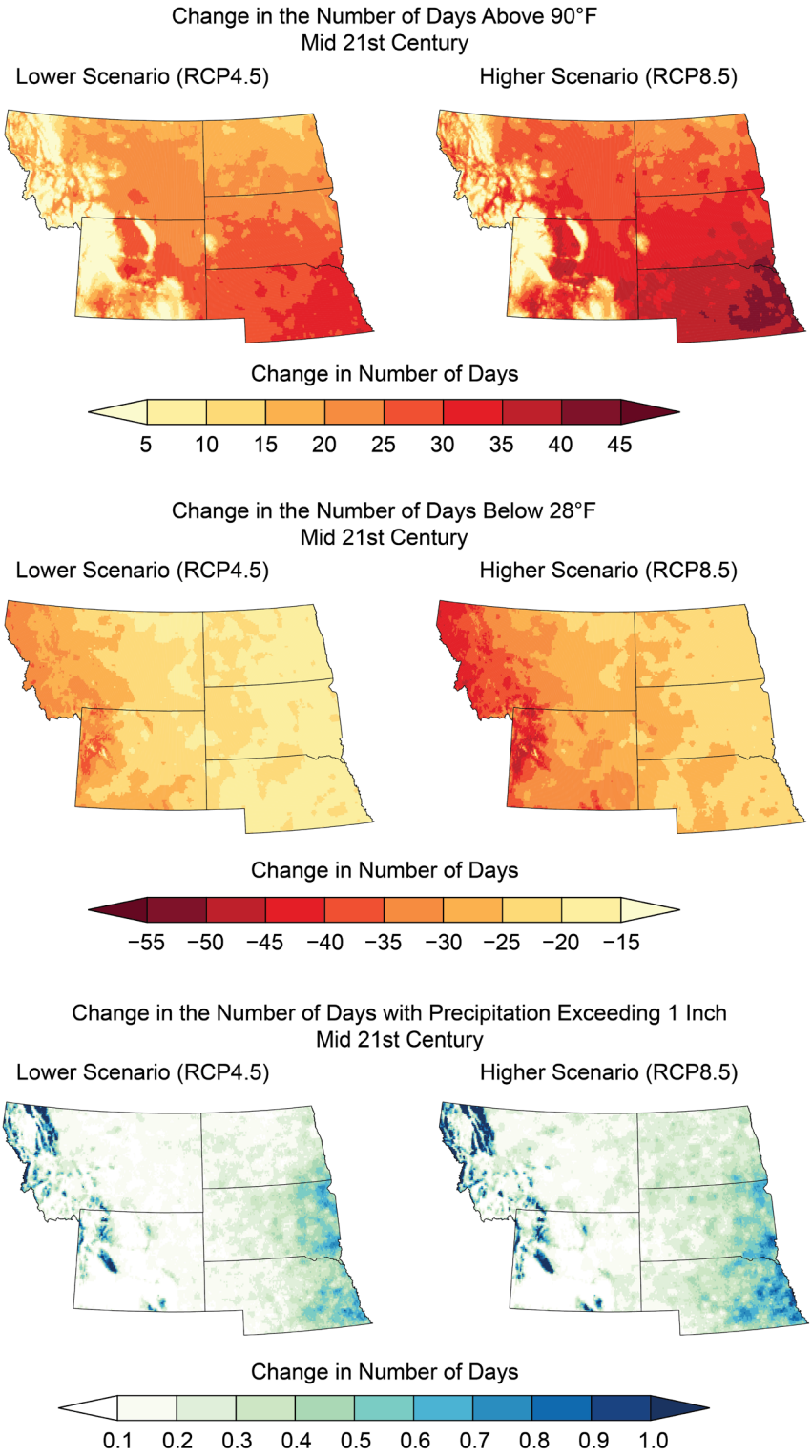
Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures. Higher temperatures, reduced snow cover, and more variable precipitation will make it increasingly challenging to manage the region's valuable wetlands, rivers, and snow-dependent ecosystems. In the mountains of western Wyoming and western Montana, the fraction of total water in precipitation that falls as snow is expected to decline by 25% to 40% by 2100 under a higher scenario (RCP8.5), which would negatively affect the region's winter recreation industry. At lower-elevation areas of the Northern Great Plains, climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands, and the diverse species and recreational opportunities they support.

Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, and stored water, and to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change. Railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion. Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources. These cost increases will either lead to lower production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.

Indigenous peoples in the region are observing changes to climate, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies, medicines, and health and well-being. Because some tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still directly reliant on natural resources, they are among the most at risk to climate change.

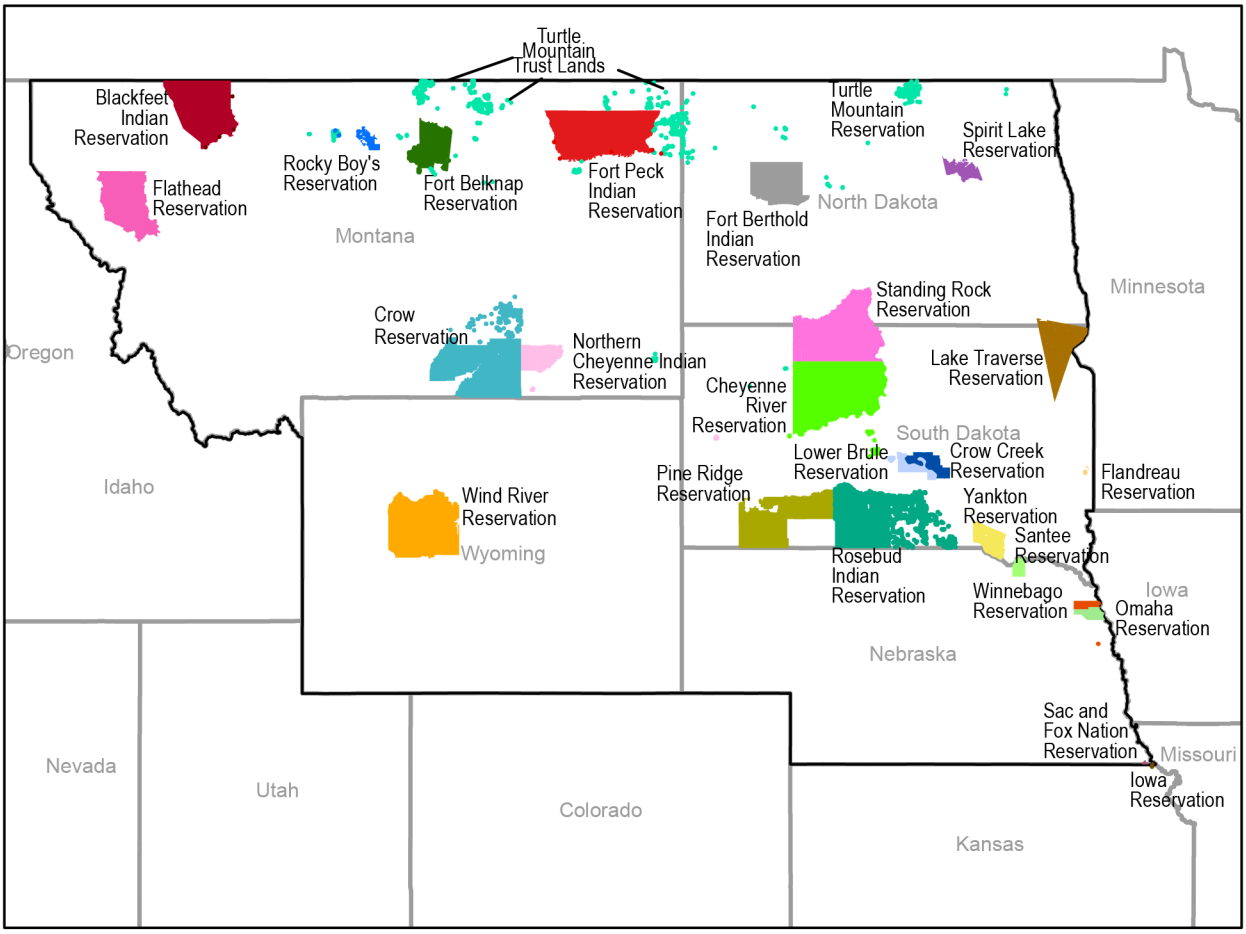
For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/northern-great-plains.

Projected Changes in Very Hot Days, Cool Days, and Heavy Precipitation



Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost), and (bottom) heavy precipitation events (the annual number of days with greater than 1 inch of rainfall; areas in white do not normally experience more than 1 inch of rainfall in a single day). Projections are shown for the middle of the 21st century (2036–2065) as compared to the 1976–2005 average under the lower and higher scenarios (RCP4.5 and RCP8.5). *From Figure 22.2 (Sources: NOAA NCEI and CICS-NC)*.

Northern Great Plains Tribal Lands



The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains is described in Chapter 15: Tribes and Indigenous Peoples. *From Figure 22.7 (Sources: created by North Central Climate Science Center [2017] with data from the Bureau of Indian Affairs, Colorado State University, and USGS National Map)*.

23 Southern Great Plains

Whooping cranes in the Aransas National Wildlife Refuge in Texas

Key Message 1

Food, Energy, and Water Resources

Quality of life in the region will be compromised as increasing population, the migration of individuals from rural to urban locations, and a changing climate redistribute demand at the intersection of food consumption, energy production, and water resources. A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water.

Key Message 2

Infrastructure

The built environment is vulnerable to increasing temperature, extreme precipitation, and continued sea level rise, particularly as infrastructure ages and populations shift to urban centers. Along the Texas Gulf Coast, relative sea level rise of twice the global average will put coastal infrastructure at risk. Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts.

Key Message 3

Ecosystems and Ecosystem Services

Terrestrial and aquatic ecosystems are being directly and indirectly altered by climate change. Some species can adapt to extreme droughts, unprecedented floods, and wildfires from a changing climate, while others cannot, resulting in significant impacts to both services and people living in these ecosystems. Landscape-scale ecological services will increase the resilience of the most vulnerable species.

Key Message 4

Human Health

Health threats, including heat illness and diseases transmitted through food, water, and insects, will increase as temperature rises. Weather conditions supporting these health threats are projected to be of longer duration or occur at times of the year when these threats are not normally experienced. Extreme weather events with resultant physical injury and population displacement are also a threat. These threats are likely to increase in frequency and distribution and are likely to create significant economic burdens. Vulnerability and adaptation assessments, comprehensive response plans, seasonal health forecasts, and early warning systems can be useful adaptation strategies.

Key Message 5

Indigenous Peoples

Tribal and Indigenous communities are particularly vulnerable to climate change due to water resource constraints, extreme weather events, higher temperature, and other likely public health issues. Efforts to build community resilience can be hindered by economic, political, and infrastructure limitations, but traditional knowledge and intertribal organizations provide opportunities to adapt to the potential challenges of climate change.

The Southern Great Plains experiences weather that is dramatic and consequential; from hurricanes and flooding to heat waves and drought, its 34 million people, their infrastructure, and economies are often stressed, greatly impacting socioeconomic systems. The quality of life for the region's residents is dependent upon resources and natural systems for the sustainable provision of our basic needs—food, energy, and water. Extreme weather and climate events have redistributed demands for consumption, production, and supply across the region. Adaptation strategies that integrate climate services and early warning systems are improving our abilities to develop sustainable infrastructure and increase agricultural production, yet include the flexibility needed to embrace any changing demand patterns.

Regional adaptation efforts that harden or relocate critical infrastructure will reduce the risk of climate change impacts. Redesigns of coastal infrastructure and the use of green/gray methodologies are improving future coastal resilience. Energy industry reinvention is ensuring operations and reliability during extreme climatic events. Increasingly robust considerations of economic resilience allow us to anticipate risk, evaluate how that risk can affect our needs, and build a responsive adaptive capacity.

With climate change, terrestrial and aquatic ecosystems, and species within them, have winners and losers. Those that can adapt are "increasers," while others cannot, resulting in impacts to traditional services and the livelihoods of the people who depend on those resources. The warming of coastal bay waters has been documented since at least the 1980s, and those increases in water temperature directly affect water quality, leading to hypoxia, harmful algal blooms, and fish

kills—thus lowering the productivity and diversity of estuaries. Natural wetlands like the playa lakes in the High Plains, which have served for centuries as important habitat for migrating waterfowl, are virtually nonexistent during drought.

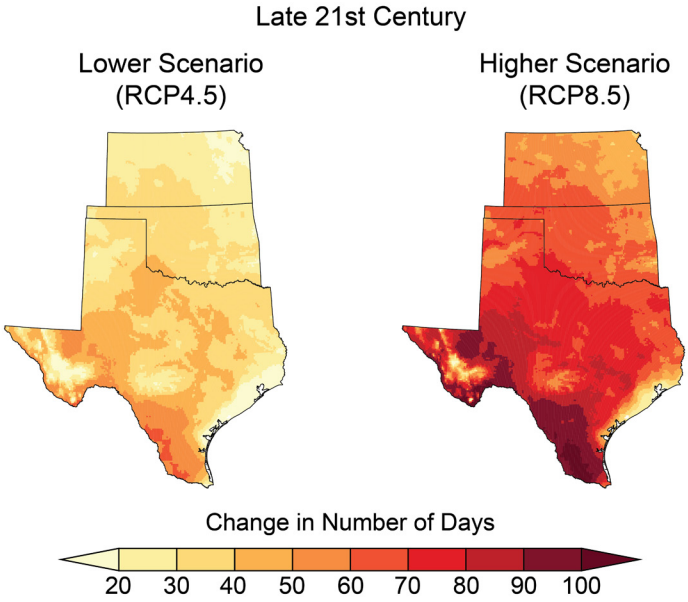
Direct human health threats follow a similar pattern of species within our natural ecosystems. Extreme weather results in both direct and indirect impacts to people; physical injury and population displacement are anticipated to result with climate change. Heat illness and diseases transmitted through food, water, and insects increase human risk as temperature rises. Acute awareness of these future impacts allows us to plan for the most vulnerable and adapt through response plans, health forecasting, and early warning strategies, including those that span transboundary contexts and systems.

The impacts of climate change in general become more acute when considering tribal and Indigenous communities. Resilience to climate change will be hindered by economic, political, and infrastructure limitations for these groups; at the same time, connectivity of the tribes and Indigenous communities offers opportunities for teaching adaptably through their cultural means of applying traditional knowledge and intertribal organization. These well-honed connections of adapting through the centuries may help all of us learn how to offset the impacts and potential challenges of climate change.

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify. Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather, including an increase in the instances of larger hail sizes in the region by 2040, but changes are unlikely to be uniform across the region, and additional research is needed.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/southern-great-plains.

Projected Increase in Number of Days Above 100°F



Under both lower- and higher-scenario climate change projections, the number of days exceeding 100°F is projected to increase markedly across the Southern Great Plains by the end of the century (2070–2099 as compared to 1976–2005). *From Figure 23.4 (Sources: NOAA NCEI and CICS-NC).*

24 Northwest

Four Lakes basin in White Cloud Peaks, Sawtooth National Forest, Idaho

Key Message 1

Natural Resource Economy

Climate change is already affecting the Northwest's diverse natural resources, which support sustainable livelihoods; provide a robust foundation for rural, tribal, and Indigenous communities; and strengthen local economies. Climate change is expected to continue affecting the natural resource sector, but the economic consequences will depend on future market dynamics, management actions, and adaptation efforts. Proactive management can increase the resilience of many natural resources and their associated economies.

Key Message 2

Natural World and Cultural Heritage

Climate change and extreme events are already endangering the well-being of a wide range of wildlife, fish, and plants, which are intimately tied to tribal subsistence culture and popular outdoor recreation activities. Climate change is projected to continue to have adverse impacts on the regional environment, with implications for the values, identity, heritage, cultures, and quality of life of the region's diverse population. Adaptation and informed management, especially culturally appropriate strategies, will likely increase the resilience of the region's natural capital.

Key Message 3

Infrastructure

Existing water, transportation, and energy infrastructure already face challenges from flooding, landslides, drought, wildfire, and heat waves. Climate change is projected to increase the risks from many of these extreme events, potentially compromising the reliability of water supplies, hydropower, and transportation across the region. Isolated communities and those with systems that lack redundancy are the most vulnerable. Adaptation strategies that address more than one sector, or are coupled with social and environmental co-benefits, can increase resilience.

Key Message 4

Health

Organizations and volunteers that make up the Northwest's social safety net are already stretched thin with current demands. Healthcare and social systems will likely be further challenged with the increasing frequency of acute events, or when cascading events occur. In addition to an increased likelihood of hazards and epidemics, disruptions in local economies and food systems are projected to result in more chronic health risks. The potential health co-benefits of future climate mitigation investments could help to counterbalance these risks.

Key Message 5

Frontline Communities

Communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged. These communities generally prioritize basic needs, such as shelter, food, and transportation; frequently lack economic and political capital; and have fewer resources to prepare for and cope with climate disruptions. The social and cultural cohesion inherent in many of these communities provides a foundation for building community capacity and increasing resilience.

Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The region is known for clean air, abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Climate change, including gradual changes to the climate and in extreme climatic events, is already affecting these valued aspects of the region, including the natural resource sector, cultural identity and quality of life, built infrastructure systems, and the health of Northwest residents. The communities on the front lines of climate change—tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged—are experiencing the first, and often the worst, effects.

In the Third National Climate Assessment, the Key Messages for the Northwest focused on projected climate impacts to the region. These impacts, many of which are now better understood in the scientific literature, remain the primary climate concerns over the coming decades. In this updated assessment, the Key Messages explore how climate change could affect the interrelationships between the environment and the people of the Northwest. The extreme weather events of 2015 provide an excellent opportunity to explore projected changes in baseline climate conditions for the Northwest. The vast array of climate impacts that occurred over this record-breaking warm and dry year, coupled with the impacts of a multiyear drought, provide an enlightening glimpse into what may be more commonplace under a warmer future climate. Record-low snowpack led to water scarcity and large wildfires that negatively affected farmers, hydropower, drinking water, air quality, salmon, and recreation. Warmer than normal ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom that adversely affected the region's fisheries and shellfish harvests.

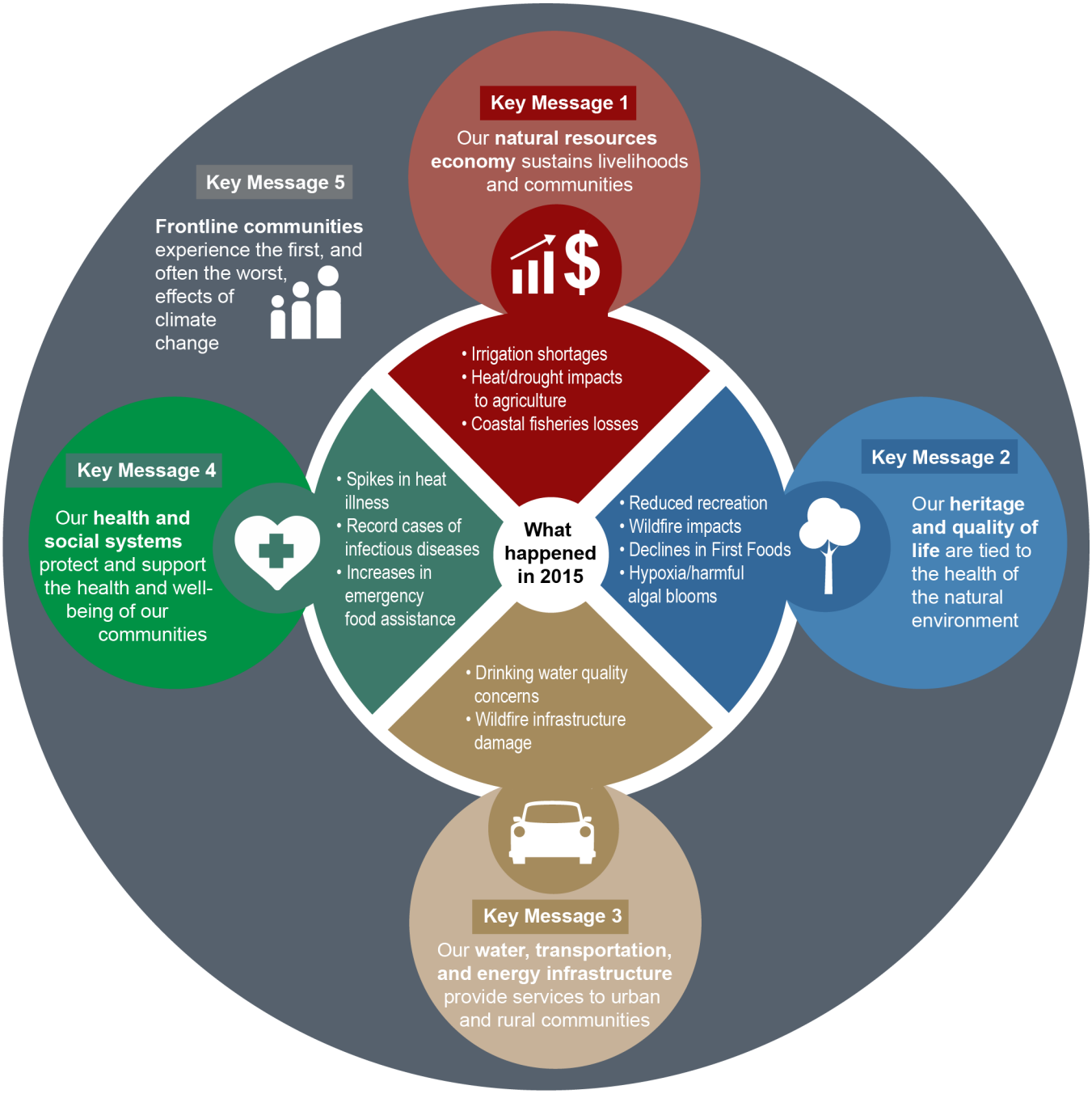
Strong climate variability is likely to persist for the Northwest, owing in part to the year-to-year and decade-to-decade climate variability associated with the Pacific Ocean. Periods of prolonged drought are projected to be interspersed with years featuring heavy rainfall driven by powerful atmospheric rivers and strong El Niño winters associated with storm surge, large waves, and coastal erosion. Continued changes in the ocean environment, such as warmer waters, altered chemistry, sea level rise, and shifts in the marine ecosystems are also expected. These changes would affect the Northwest's natural resource economy, cultural heritage, built infrastructure, and recreation as well as the health and welfare of Northwest residents.

The Northwest has an abundance of examples and case studies that highlight climate adaptation in progress and in practice—including creating resilient agro-ecosystems that reduce climate-related risks while meeting economic, conservation, and adaptation goals; using "green" or hybrid "green and gray" infrastructure solutions that combine nature-based solutions with more traditional engineering approaches; and building social cohesion and strengthening social networks in frontline communities to assist in meeting basic needs while also increasing resilience to future climate stressors. Many of the case studies in this chapter demonstrate the importance of co-producing adaptation efforts with

scientists, resource managers, communities, and decision-makers as the region prepares for climate change impacts across multiple sectors and resources.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/northwest.

Climate Change Will Impact Key Aspects of Life in the Northwest



The climate-related events of 2015 provide a glimpse into the Northwest's future, because the kinds of extreme events that affected the Northwest in 2015 are projected to become more common. The climate impacts that occurred during this record-breaking warm and dry year highlight the close interrelationships between the climate, the natural and built environment, and the health and well-being of the Northwest's residents. *From Figure 24.2 (Source: USGCRP)*.

25 Southwest

Low water levels in Lake Mead

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Key Message 5

Energy

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

Key Message 6

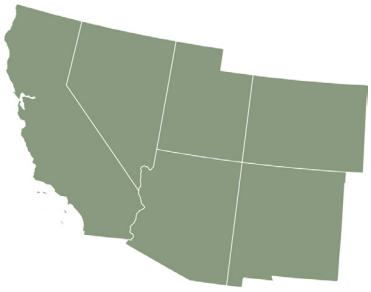
Food

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

Key Message 7

Human Health

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



The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Water for people and nature in the Southwest region has declined during droughts, due in part to human-caused climate change. Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume, a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture.

The reduction of water volume in both Lake Powell and Lake Mead increases the risk of water shortages across much of the Southwest. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. In response to the recent California drought, the state implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices. As a result, the people of the state reduced water use 25% from 2014 to 2017.

Exposure to hotter temperatures and heat waves already leads to heat-associated deaths in Arizona and California. Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution. Given the proportion of the U.S. population in the Southwest region, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.

Analyses estimated that the area burned by wildfire across the western United States from 1984 to 2015 was twice what would have burned had climate change not occurred. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation). Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due, in part, to climate change. Allowing naturally ignited fires to burn in wilderness areas and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change. Reducing greenhouse gas emissions globally can also reduce ecological vulnerabilities.

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016. Climate change caused most of this rise by melting of land ice and thermal expansion of ocean water. Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. Ocean water acidity off the coast of California increased 25% to 40% (decreases of 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to 2014 due to increasing concentrations of atmospheric carbon dioxide from human activities. The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change. The event led to the mass stranding of sick and starving birds and sea lions, and shifts of red crabs and tuna into the region. The ecosystem disruptions contributed to closures of commercially important fisheries.

Agricultural irrigation accounts for approximately three-quarters of water use in the Southwest region, which grows half of the fruits, vegetables, and nuts and most of the wine grapes, strawberries, and lettuce for the

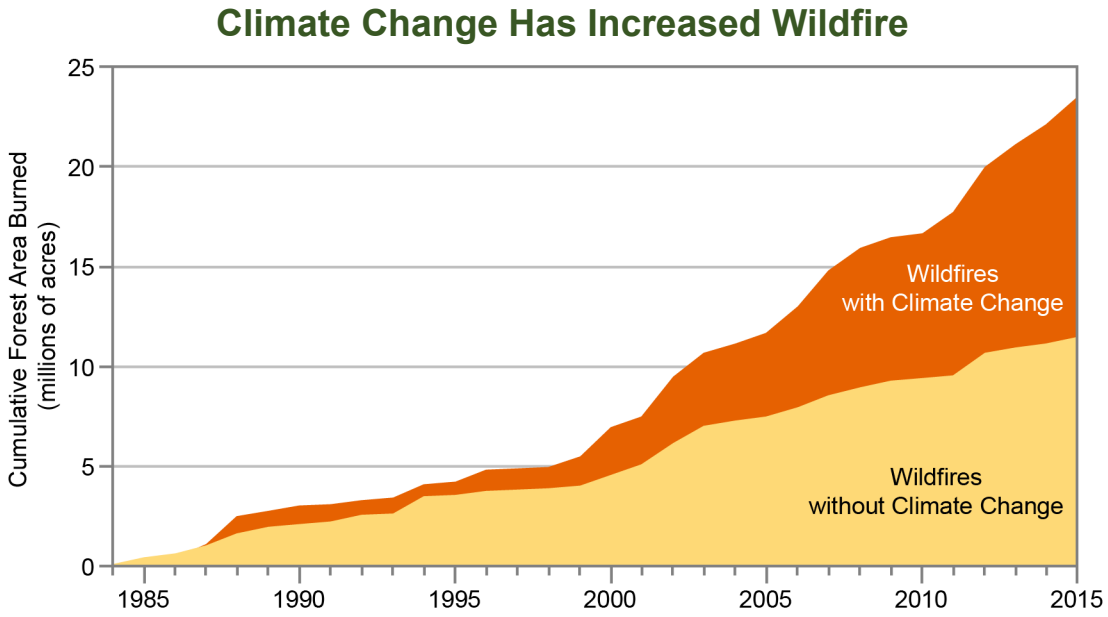
United States. Increasing heat stress during specific phases of the plant life cycle can increase crop failures.

Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands. In response to climate change, Indigenous peoples in the region are developing new adaptation and mitigation actions.

The severe drought in California, intensified by climate change, reduced hydroelectric generation two-thirds from 2011 to 2015.

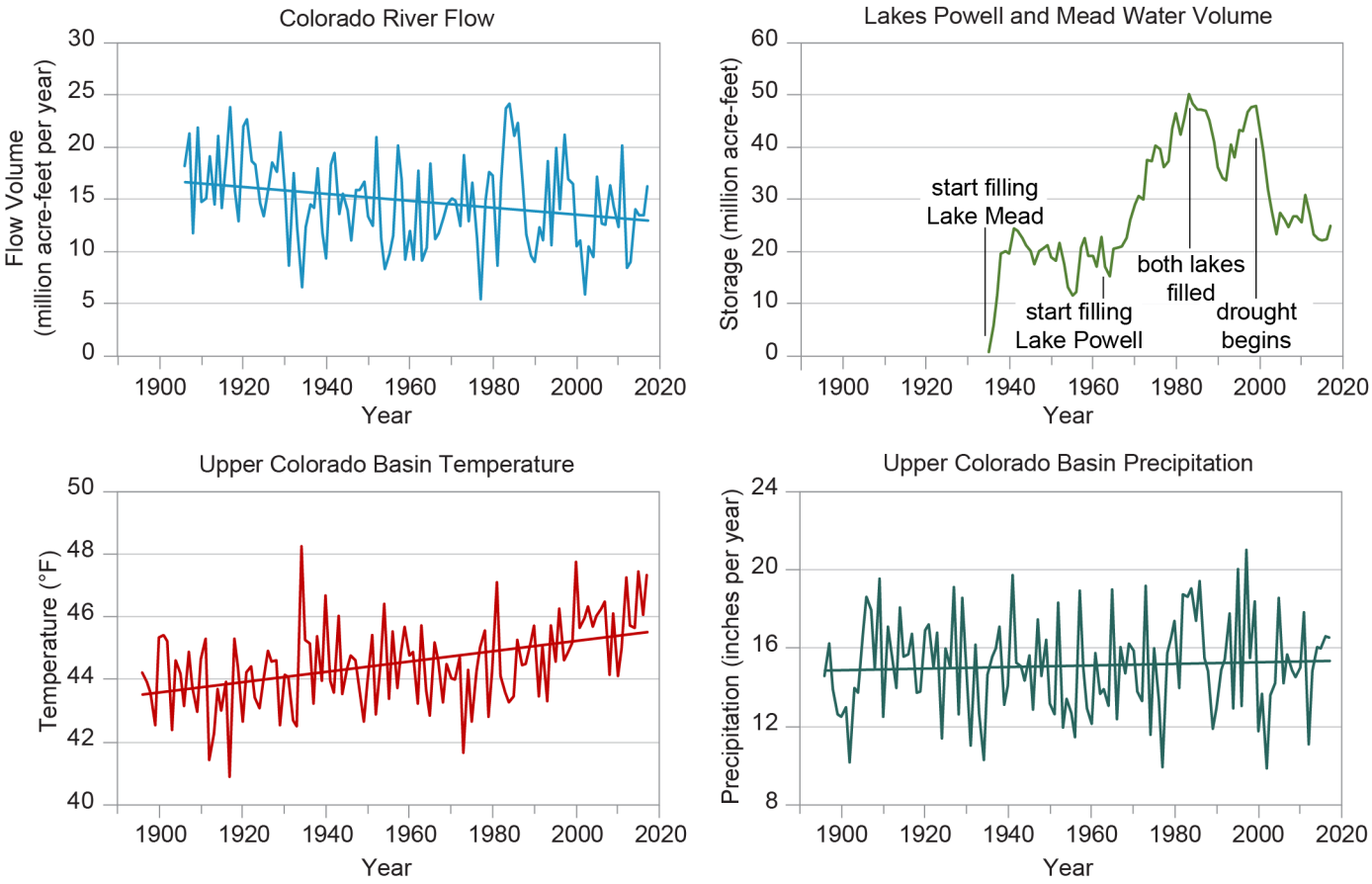
The efficiency of all water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest by 2050. Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/southwest.



The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. *From Figure 25.4 (Source: adapted from Abatzoglou and Williams 2016)*.

Severe Drought Reduces Water Supplies in the Southwest



Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. *From Figure 25.3 (Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 20 Jun 2018).*

26 Alaska

Anchorage, Alaska

Key Message 1

Marine Ecosystems

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

Key Message 2

Terrestrial Processes

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

Key Message 3

Human Health

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

Key Message 4

Indigenous Peoples

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

Key Message 5

Economic Costs

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

Key Message 6

Adaptation

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

Alaska is the largest state in the Nation, almost one-fifth the size of the combined lower 48 United States, and is rich in natural capital resources. Alaska is often identified as being on the front lines of climate change since it is warming faster than any other state and faces a myriad of issues associated with a changing climate. The cost of infrastructure damage from a warming climate is projected to be very large, potentially ranging from $110 to $270 million per year, assuming timely repair and maintenance.

Although climate change does and will continue to dramatically transform the climate and environment of the Arctic, proactive adaptation in Alaska has the potential to reduce costs associated with these impacts. This includes the dissemination of several tools, such as guidebooks to support adaptation planning, some of which focus on Indigenous communities. While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

As the climate continues to warm, there is likely to be a nearly sea ice-free Arctic during the summer by mid-century. Ocean acidification is an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions

and negatively affects organisms. Climate change will likely affect management actions and economic drivers, including fisheries, in complex ways. The use of multiple alternative models to appropriately characterize uncertainty in future fisheries biomass trajectories and harvests could help manage these challenges. As temperature and precipitation increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost is expected to continue, with associated impacts to infrastructure, river and stream discharge, water quality, and fish and wildlife habitat.

Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat in the future and in some cases requiring entire communities or portions of communities to relocate to safer terrain. The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States. Climate change exerts indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting disease ecology and food security, especially in rural communities.

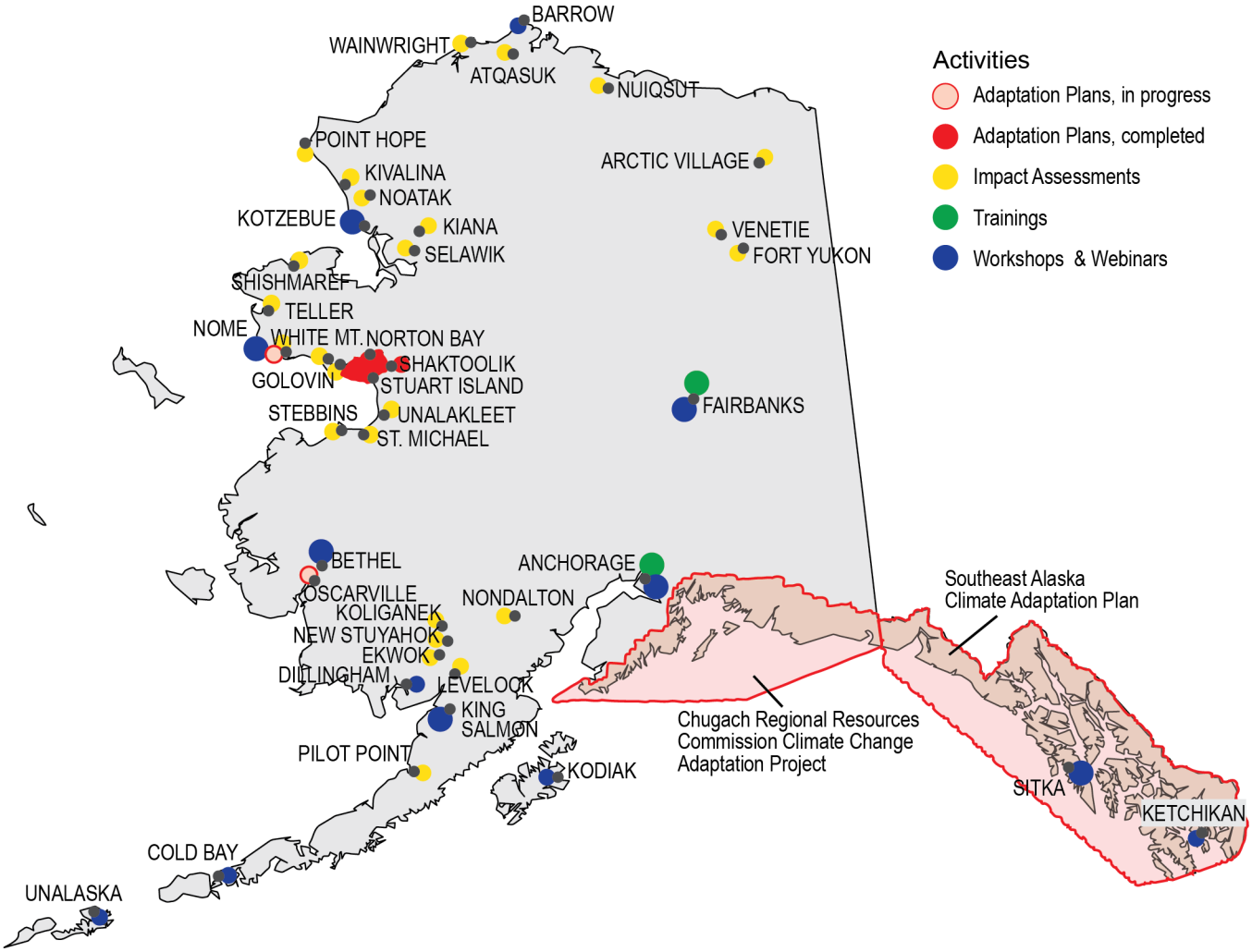
Alaska's rural communities are predominantly inhabited by Indigenous peoples who may be disproportionately vulnerable to socioeconomic and environmental change; however, they also have rich cultural traditions of resilience and adaptation. The impacts of climate change will likely affect all aspects of Alaska Native societies, from nutrition, infrastructure, economics, and health consequences to language, education, and the communities themselves.

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

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

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/alaska.

Adaptation Planning in Alaska



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

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

Honolulu, Hawai‘i

Key Message 1

Threats to Water Supplies

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

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

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

Key Message 3

Coastal Communities and Systems

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

Key Message 4

Oceans and Marine Resources

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

Key Message 5

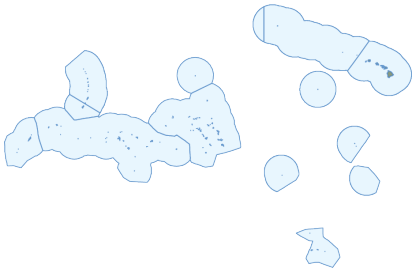
Indigenous Communities and Knowledge

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

Key Message 6

Cumulative Impacts and Adaptation

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



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

A prevalent cause of year-to-year changes in climate patterns around the globe and in the Pacific Islands region is the El Niño–Southern Oscillation (ENSO). The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds. It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both El Niño and La Niña extremes in this century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).

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

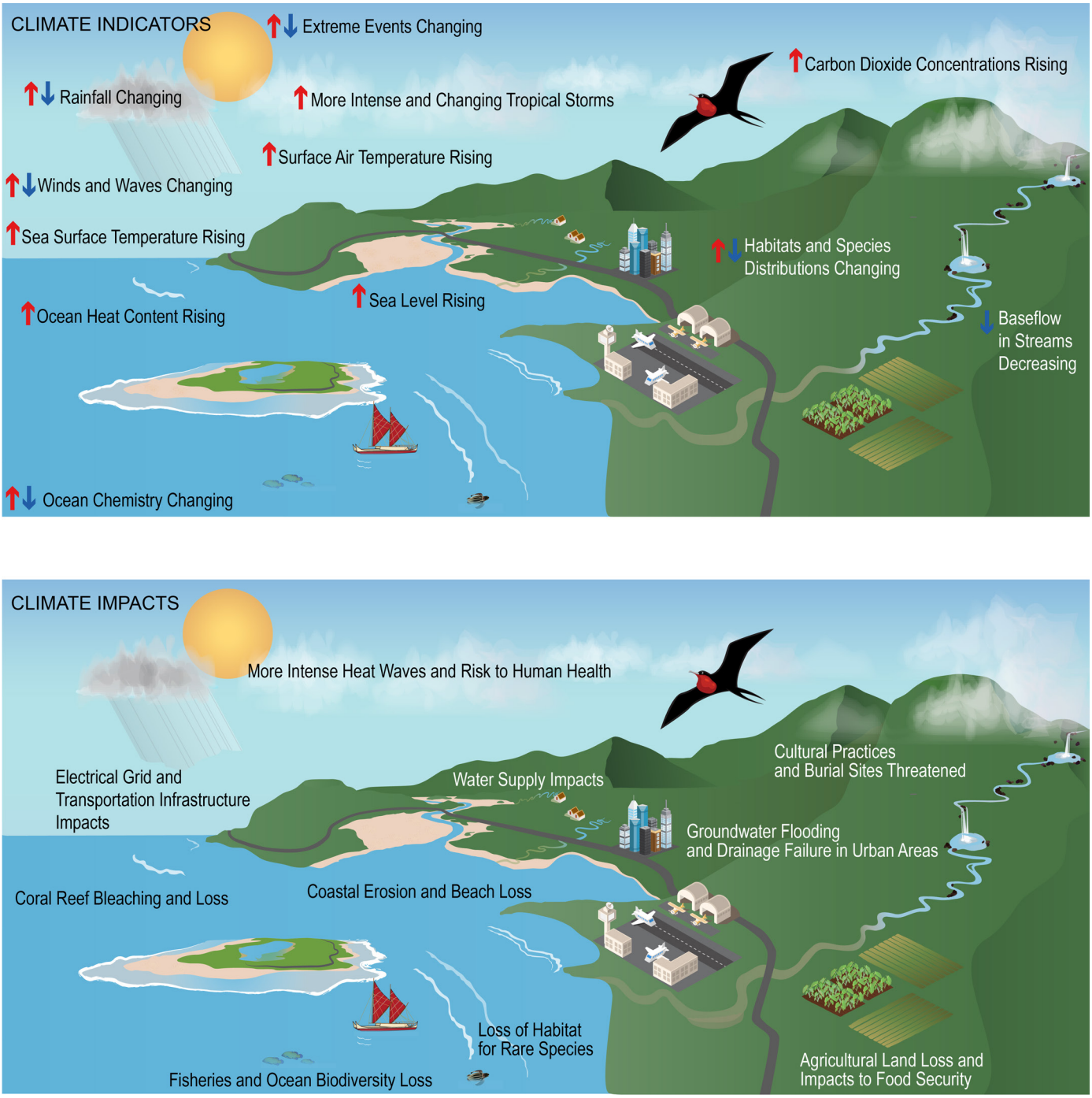
The impacts of sea level rise in the Pacific include coastal erosion, episodic flooding, permanent inundation, heightened exposure to marine hazards, and saltwater intrusion to surface water and groundwater systems. Sea level rise will disproportionately affect the tropical Pacific and potentially exceed the global average.

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

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

Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation as well as other

Climate Indicators and Impacts

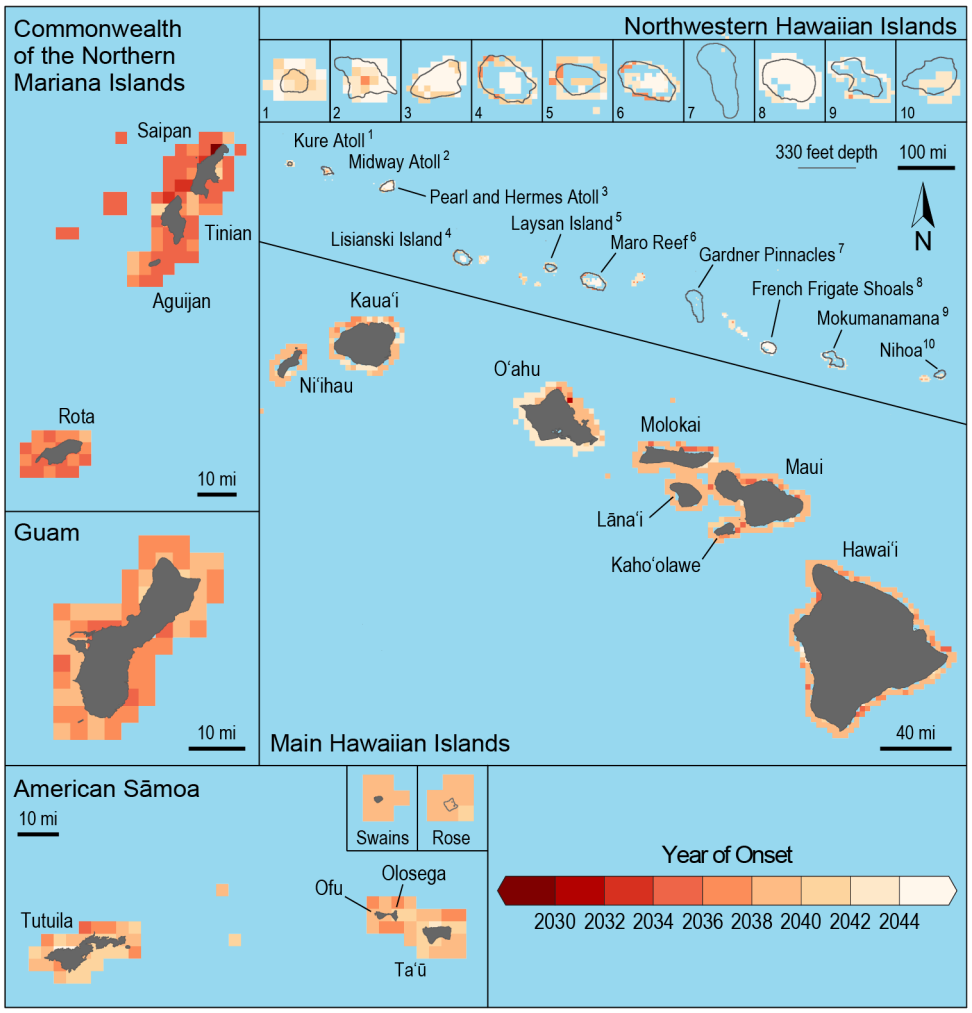


Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in Hawai'i and the U.S.-Affiliated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

climate-related impacts. Social cohesion is already strong in many communities, making it possible to work together to take action. Early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/hawaii-pacific.

Projected Onset of Annual Severe Coral Reef Bleaching



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

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18. Northeast: Bartram Bridge in Pennsylvania. *© Thomas James Caldwell/Flickr. CC BY-SA 2.0, https://creativecommons.org/licenses/by-sa/2.0/legalcode*.

19. Southeast: Red mangrove in Titusville, Florida. *© Katja Schulz/Flickr. CC BY 2.0, https://creativecommons.org/licenses/by/2.0/legalcode*.

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22. N. Great Plains: Cameron, Montana. *Paul Cross/U.S. Geological Survey.*

23. S. Great Plains: Whooping cranes in the Aransas National Wildlife Refuge in Texas. *Jon Noll/U.S. Department of Agriculture.*

24. Northwest: Four Lakes basin in White Cloud Peaks, Sawtooth National Forest, Idaho. *Mark Lisk/USDA Forest Service.*

25. Southwest: Low water levels in Lake Mead. *© Wayne Hsieh/Flickr. CC BY-NC 2.0, https://creativecommons.org/licenses/by-nc/2.0/legalcode*.

26. Alaska: Anchorage, Alaska. *© Rocky Grimes/istock/Getty Images*.

27. Hawai'i & Pacific Islands: Honolulu, Hawai'i. *NOAA Teacher at Sea Program, NOAA Ship Hi'ialakai.*

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Responses

Executive Summaries

28 Reducing Risks Through Adaptation Actions

Seawall surrounding Kivalina, Alaska

Key Message 1

Adaptation Implementation Is Increasing

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

Key Message 2

Climate Change Outpaces Adaptation Planning

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

Key Message 3

Adaptation Entails Iterative Risk Management

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

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

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

Key Message 5

New Approaches Can Further Reduce Risk

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

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

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

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

property values, land-use plans, disaster response preparations, supply chains, and cropland and forest management.

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

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

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

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

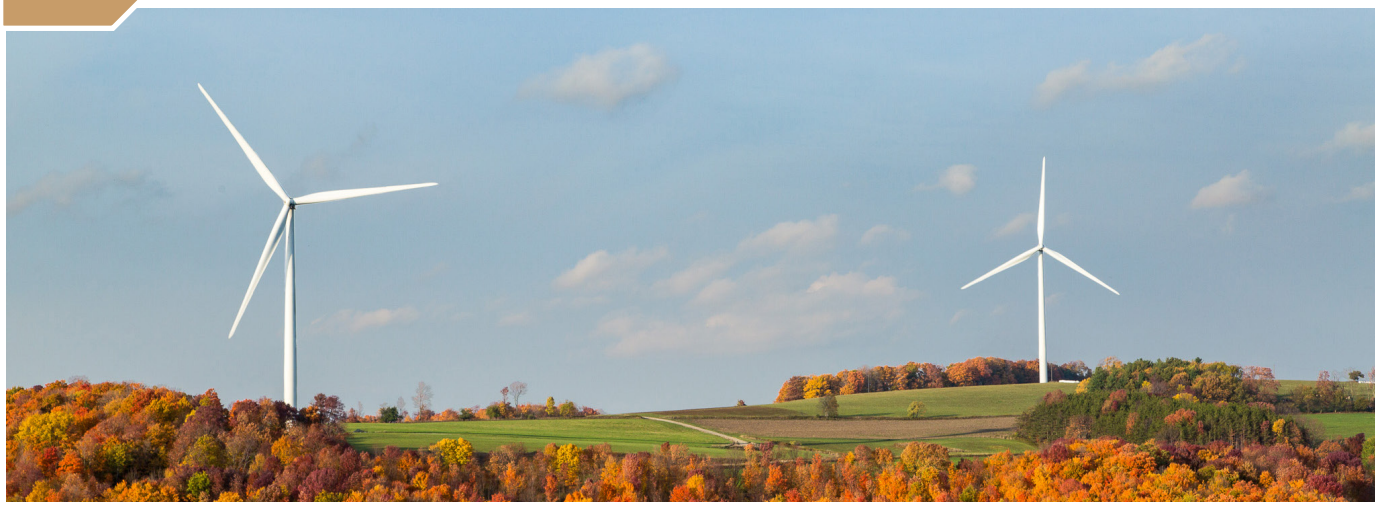
A significant portion of climate risk can be addressed by mainstreaming; that is, integrating climate adaptation into existing organizational and sectoral investments, policies, and practices, such as planning, budgeting, policy development, and operations and maintenance. Mainstreaming of climate adaptation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

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/adaptation.

Five Adaptation Stages and Progress

The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. *From Figure 28.1 (Source: adapted from National Research Council, 2010. Used with permission from the National Academies Press, © 2010, National Academy of Sciences. Image credits, clockwise from top: National Weather Service; USGS; Armando Rodriguez, Miami-Dade County; Dr. Neil Berg, MARISA; Bill Ingalls, NASA).*

29 Reducing Risks Through Emissions Mitigation



Jasper, New York

Key Message 1

Mitigation-Related Activities Within the United States

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

Key Message 2

The Risks of Inaction

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

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

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

Key Message 4

Interactions Between Mitigation and Adaptation

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

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

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

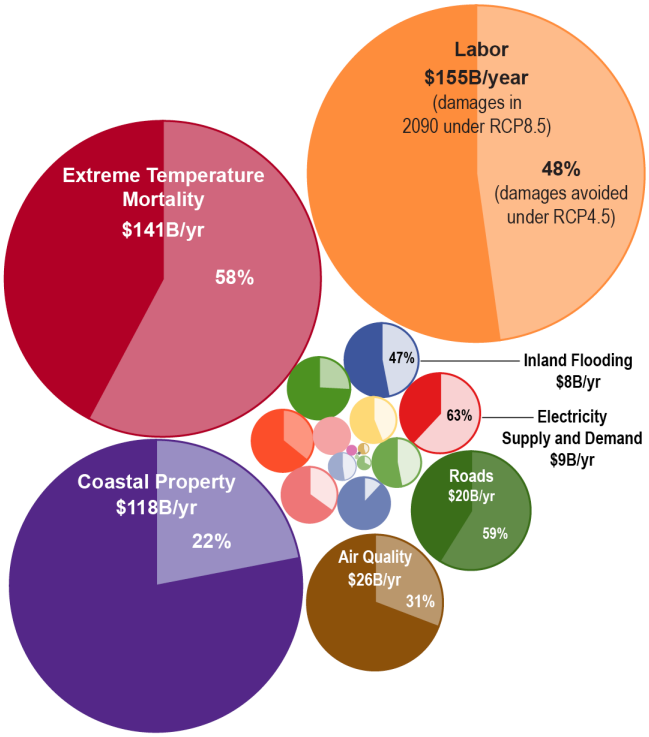
Recent studies also show that many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions. While the difference in climate outcomes between scenarios is more modest through the first half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

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population. Physical damages to coastal property and transportation infrastructure are particularly sensitive to adaptation assumptions, with proactive measures estimated to be capable of reducing damages by large fractions. Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and adaptation activities can be considered complementary strategies. However, adaptation can require large up-front costs and long-term commitments for maintenance, and uncertainty exists in some sectors regarding the

applicability and effectiveness of adaptation in reducing risk. Interactions between adaptation and mitigation strategies can result in benefits or adverse consequences. While uncertainties still remain, advancements in the modeling of climate and economic impacts, including current understanding of adaptation pathways, are increasingly providing new capabilities to understand and quantify future effects.

For full chapter, including references and Traceable Accounts, see https://nca2018.globalchange.gov/chapter/mitigation.

Projected Damages and Potential for Risk Reduction by Sector



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

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

Banner Photo Credits

28. Adaptation: Seawall surrounding Kivalina, Alaska. *© ShoreZone. CC BY 3.0, https://creativecommons.org/licenses/by/3.0/legalcode*.

29. Mitigation: Jasper, New York. *© John Getchel/Flickr. CC BY-NC 2.0, https://creativecommons.org/licenses/by-nc/2.0/legalcode*.

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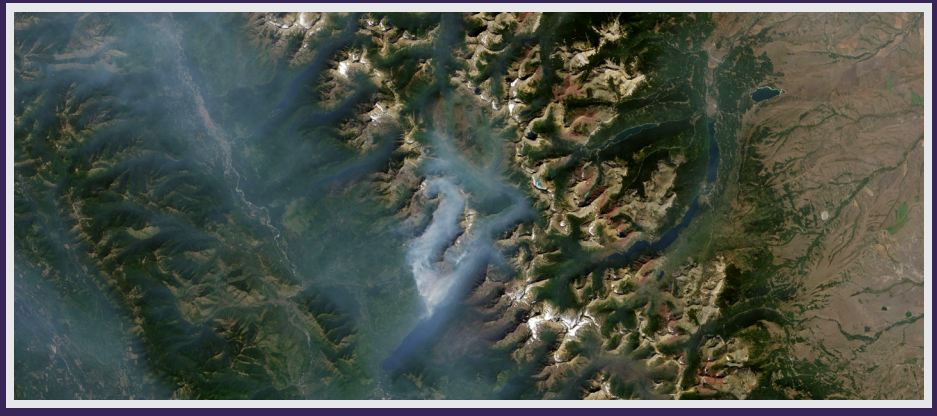

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