Fifth National Climate Assessment



U.S. Global Change Research Program

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Cover image

Two volunteers help demonstrate and install solar panels in Highland Park, Michigan, in May 2021. The event was hosted by the local nonprofit Soulardarity, which teaches local residents about solar power, installs solar-powered streetlights that also provide wireless internet access, and helps local communities build a just and equitable energy system. Adopting energy storage with decentralized solutions, such as microgrids or off-grid systems, can promote energy equity in overburdened communities. Photo credit: Nick Hagen.

Fifth National Climate Assessment



U.S. Global Change Research Program

The Fifth National Climate Assessment is the US Government's preeminent report on climate change impacts, risks, and responses. It is a congressionally mandated interagency effort that provides the scientific foundation to support informed decision-making across the United States.

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Startlement

by Ada Limón, 24th Poet Laureate Consultant in Poetry at the Library of Congress

It is a forgotten pleasure, the pleasure
of the unexpected blue-bellied lizard

skittering off his sun spot rock, the flicker
of an unknown bird by the bus stop.

To think, perhaps, we are not distinguishable
and therefore no loneliness can exist here.

Species to species in the same blue air, smoke—
wing flutter buzzing, a car horn coming.

So many unknown languages, to think we have
only honored this strange human tongue.

If you sit by the riverside, you see a culmination
of all things upstream. We know now,

we were never at the circle's center, instead
all around us something is living or trying to live.

The world says, What we are becoming, we are
becoming together.

The world says, One type of dream has ended
and another has just begun.

The world says, Once we were separate,
and now we must move in unison.

A poem written for the Fifth National Climate Assessment.
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Jack Kaye, National Aeronautics and Space Administration
Maria Uhle, National Science Foundation
Kirk Johnson, Smithsonian Institution
Noel P. Gurwick, US Agency for International Development

USGCRP National Climate Assessment (NCA) Coordination Office

NCA Leadership

Allison R. Crimmins, NCA Director
Christopher W. Avery, NCA Chief of Staff
J. Michael Kuperberg, Acting NCA Director (through June 2021)

Chapter Points of Contact

Samantha Basile, Lead Carbon Cycle Specialist
David J. Dokken, Senior International Assessment Lead
Leo Goldsmith, Climate and Health Specialist
Aaron M. Grade, NCA Staff Scientist
Joshua Hernandez, NCA Staff Specialist
Katia Kontar, International Global Change Science Lead
Yishen Li, Water Cycle Science Coordinator
Fredric Lipschultz, Senior Staff Scientist
Allyza R. Lustig, Senior NCA Staff Manager
Austin A. Scheetz, Social Sciences Specialist
Reid A. Sherman, Climate Adaptation Lead
Susan C. Aragon-Long , Senior Science Coordinator / USGS Liaison to USGCRP (through January 2022)
Drew Story, Global Change Science Lead (through July 2022)

Communications

Bradley Akamine, Chief Digital Information Officer
Laurie Howell, Engagement and Communications Lead
Alexa K. Jay, Senior Science Writer
Stephanie Lopez, Communications Specialist
Katie Reeves, Engagement and Communications Lead (through April 2023)
Charles A. Brodine, Engagement and Communications Specialist (through August 2022)

Operations and Special Projects

Ciara R. Lemery, Senior Editorial Specialist and Figure Coordinator
Sarah Abdelrahim, USGCRP Deputy Director (through March 2023)
Julie Morris, Associate Director
Nico Adams, Chief of Operations
Mathia Biggs, Operations Coordinator Lead
Alex Da Silva, Climate Change and Sustainability Analyst, ICF
D'Arcy Carlson, Climate Change and Sustainability Analyst, ICF
Alida Monaco, Climate Change and Sustainability Analyst, ICF
Emma Conrad-Rooney, Intern (through April 2023)

Peter Schultz, Vice President, ICF
Jamie Genevie, Senior Associate, ICF
Sonia Aronson, Climate Change and Sustainability Analyst, ICF (through June 2023)
Matt Greico, Climate Resilience Specialist, ICF (through October 2022)
Lynn Socha, Climate Change and Sustainability Analyst, ICF (through July 2022)
Nicole Rucker, Knauss Marine Policy Fellow (through January 2022)

Global Change Information System (GCIS)

Amrutha Elamparuthy, GCIS Lead
Zachary G. Landes, Software Developer
Reuben Aniekwu, Senior Climate Research Specialist
Shamel Wilson, Data Management Intern (from October 2022)

NOAA Technical Support Unit

David R. Easterling, Technical Support Unit Director, NOAA National Centers for Environmental Information (NCEI)
Kenneth E. Kunkel, Lead Scientist, North Carolina State University
Sara W. Veasey, NCEI Visual Communications Team Lead, NOAA NCEI
Brooke C. Stewart, Managing Editor and Lead Science Editor, North Carolina State University (through July 2023)
Thomas K. Maycock, Senior Science Editor, North Carolina State University
Jessicca Allen, Visual Communications Specialist and Lead Graphic Designer, North Carolina State University
Barbara Ambrose, Visual Communications Specialist, Mississippi State University, Northern Gulf Institute
Rocky Bilotta, Physical Scientist, NOAA NCEI
Amy V. Camper, Visual Communications Specialist, Innovative Consulting and Management Services LLC
Linda B. Copley, Software Engineer, North Carolina State University (through June 2023)
Ryan Cox, Web Developer, North Carolina State University
Jacquelyn Crossman, NOAA NCEI Librarian, MPF-ZAI
Mark R. Essig, Scientific Technical Editor, North Carolina State University
Bridgette O. Haley, Visual Communications Specialist, NOAA NCEI
Katharine M. Johnson, Web Developer and GIS Specialist, North Carolina State University
April D. Lamb, Editor, Visual Communications and Metadata Specialist, North Carolina State University
Ciara R. Lemery, Senior Editorial Specialist and Figure Coordinator, US Global Change Research Program / ICF
Angel Li, Web Developer, North Carolina State University
Liz Love-Brotak, Visual Communications Specialist, NOAA NCEI
Andrea McCarrick, Scientific Technical Editor, North Carolina State University
Laura Ohlmann, Communications Specialist, Innovative Consulting and Management Services LLC
Deborah B. Riddle, Visual Communications Specialist, NOAA NCEI
Laura E. Stevens, Research Scientist, North Carolina State University
Liqiang Sun, Research Scientist, North Carolina State University
Xia Sun, Climate Data Analyst, North Carolina State University
Xiangdong Zhang, Senior Scientist, North Carolina State University
Sarah M. Champion, Data Architect and Lead Information Quality Analyst, North Carolina State University (through December 2022)
Deborah Misch, Visual Communications Specialist (through August 2022)

UNC Asheville's National Environmental Modeling and Analysis Center

Karin Rogers, Director and Research Scientist
Matthew Geiger, Software Developer
Ian Johnson, GIS Analyst and Science Communications Associate
Jeff Bliss, Principal Software Developer
Ashlyn Shore, Science Editor

Administrative Lead Agency

Department of Commerce / National Oceanic and Atmospheric Administration

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Margaret Plumley

About This Report

The Global Change Research Act of 1990[1] mandates that the US Global Change Research Program (USGCRP) deliver a report to Congress and the President not less frequently than every four years that "integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."

The Fifth National Climate Assessment (NCA5) fulfills that mandate by delivery of this Assessment and provides the scientific foundation to support informed decision-making across the United States. By design, much of the development of NCA5 built upon the approaches and processes used to create the Fourth National Climate Assessment (NCA4),[2] with a goal of continuously advancing an inclusive, diverse, and sustained process for assessing and communicating scientific knowledge on the impacts, risks, and vulnerabilities associated with a changing global climate (App. 1).

The findings in this report are based on a comprehensive review and assessment of information sources determined to meet the standards and documentation required under the Information Quality Act and the Foundations for Evidence-Based Policymaking Act of 2018 (App. 2), including peer-reviewed literature, other literature, Indigenous Knowledge, other expert and local knowledge, and climate data processed and prepared for authors by NOAA's Technical Support Unit (TSU; see Guide to the Report section below and App. 3).

NCA5 was thoroughly reviewed by Federal Government experts, external experts, and the public multiple times throughout the report development process. An expert external review was performed by an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine.[3] Additional information on the development of this Assessment can be found in Appendix 1: Assessment Development Process.

Guide to the Report

Intended Audience

The products of the US Global Change Research Program are designed to assist the Nation and the world in understanding, assessing, predicting, and responding to human-induced and natural processes of global change. National Climate Assessments synthesize scientific information and evaluate the state of the science on climate change to inform a broad audience of decision-makers across the country. These decision-makers include national, state, local, and Tribal governments, city planners, public health officials, adaptation specialists, nurses, farmers, business owners, community organizers, researchers, water utilities, ecosystem managers, educators, students, the media, and concerned individuals who need to make timely decisions about the climate impacts they are facing. National Climate Assessments make policy-neutral and policy-relevant information accessible and actionable by relying on the expert judgment of the report authors to determine what topics are included in each chapter, to describe what we know and where uncertainties remain, and to clearly communicate the risks, responses, and opportunities associated with climate change.

Categories of Chapters and Their Scope

Overview

The Overview chapter presents the major findings of the report alongside highlights drawn from across NCA5. This chapter provides a synthesis of material from the underlying report chapters.

Physical Science Chapters

The Climate Trends and Earth Systems Processes chapters (Chs. 2, 3) assess how climate change affects physical Earth systems, with a focus on the United States, including observations and projections of climate change and discussion of how methods to understand changes in Earth systems have advanced since NCA4, which was released in November 2018.

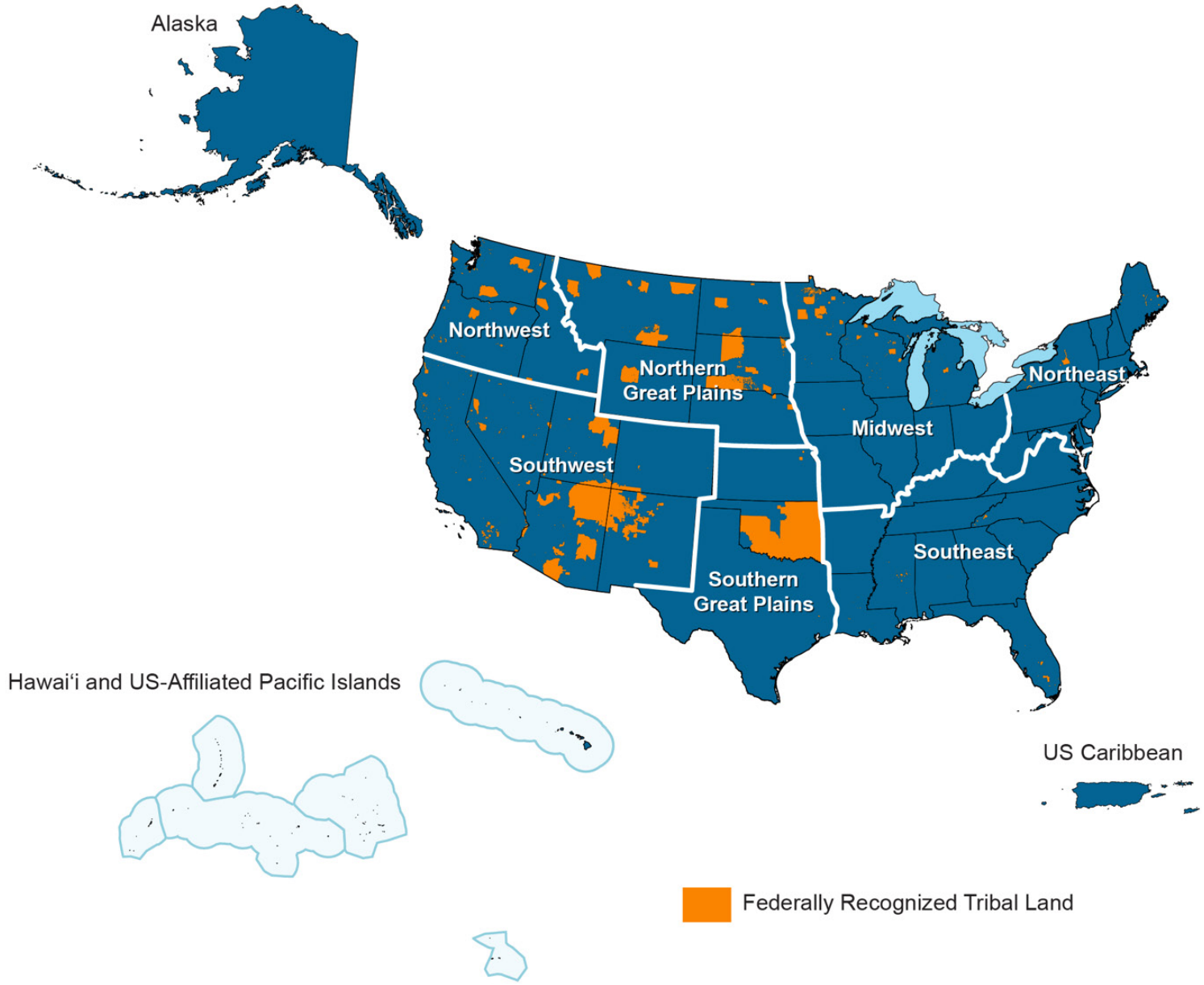
National Topic Chapters

The national topic chapters (Chs. 4–20) summarize current and future risks related to climate change and what can be done to reduce those risks for a variety of societal and economic sectors of the United States. This Assessment builds on the range of topics covered in NCA4 by adding two new chapters: Economics (Ch. 19) and Social Systems and Justice (Ch. 20).

Regional Chapters

The regional chapters (Chs. 21–30) assess current and future risks posed by climate change to each of the 10 NCA5 regions (Figure 1). These chapters provide detailed discussions of region-specific challenges, opportunities, and success stories for managing risks and impacts.

Fifth National Climate Assessment Regions



The Fifth National Climate Assessment explores subnational climate change risks, impacts, and responses in each of the 10 regions shown.

Figure 1. The map shows the 10 US regions that correspond to the 10 regional chapters of the report (Chs. 21–30). The same regional boundaries are used in text and figures throughout the Assessment to provide regional-scale information where appropriate. Adapted from USGCRP 2018.[2]

Response Chapters

The response chapters (Ch. 31: Adaptation and Ch. 32: Mitigation) assess the science of adapting to a changing climate, emissions reductions, and other efforts that together describe the US's existing and potential response to climate change, including benefits, trade-offs, targets, limitations, and best practices. The National Climate Assessment does not evaluate or recommend specific adaptation or mitigation policies.

Focus on... Features

To better address critical and timely topics with themes that span the Assessment chapters, NCA5 pioneered a new feature: a set of five "Focus on..." boxes on important cross-cutting issues. High-priority topics were nominated by authors during early development of the report; final topics were approved for inclusion by the Federal Steering Committee. Authors from multiple NCA5 chapters assessed literature, coordinated cross-report discussions, and contributed text and figures to these features.

Appendices

The first three appendices outline the development process, legal standards of scientific quality for assessing scientific information, and the climate scenarios and datasets used to support author assessment. Appendix 4 explores indicators of observed climate-related changes that support findings across NCA5. Appendix 5 is a glossary defining select terms in the context of how they are typically used across the Assessment.

Glossary of Terms

Throughout the online version of the report, definitions of terms in the glossary (App. 5) are accessible via an interactive hover-over feature where text appears with a dotted underline. Any usage of a term that differs from the glossary definition is explicitly defined within chapter text.

Artwork and Gallery

The NCA5 Art × Climate gallery showcases the work of visual artists across the country. These artworks and their accompanying descriptions speak to the causes and impacts of climate change, as well as the ways that people are responding. Submissions of visual art were collected through a public call, and finalists were selected by a jury panel of experts (App. 1). Artworks that appear throughout the PDF version of the report are denoted by a teal border. The artworks and associated artists' statements are not Assessment products and do not necessarily represent the views of the authors or USGCRP.

Structure and Format of Chapter Content

Key Messages

Chapters are centered around Key Messages, which are conclusions based on authors' expert judgment and synthesis of the assessed information sources. Many Key Messages present findings in the context of risks to natural and/or human systems. The text supporting each Key Message provides evidence, discusses implications, identifies intersections between systems or hazards, and presents examples of paths to greater resilience.

Confidence and Likelihood

Evaluating confidence and likelihood is a key part of the assessment process. As in previous Assessments, NCA5 uses specific terms to convey information about scientific confidence and certainty associated with important findings, observations, and projections. Chapter authors use a range of calibrated terms adopted from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[4] to describe the levels of **confidence** and, where appropriate, the assessment of **likelihood** associated with the statements in their Key Messages (Tables 1, 2).

- **Confidence** in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.
- **Likelihood** of a finding is based on measures of certainty expressed probabilistically; in other words, based on statistical analysis of observed or projected results or on the authors' expert judgment based on their assessment across scientific information sources.

These calibrated terms are presented in parentheses and set in *italics* after relevant phrases or sentences in the Key Messages. Statements in Key Messages that do not include either likelihood or confidence terms are intended as statements of fact. In some cases, calibrated likelihood assessments are also included in italics in the narrative text supporting Key Messages.

Table 1. Calibrated Language for Confidence Assessment

The NCA5 calibrated uncertainty language listed here and in Table 2 follows standards developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report. The confidence levels listed below are used to reflect the quantity, quality, and degree of agreement across the evidence base underpinning an assessment finding. Source: Mastrandrea et al. 2011[4]

Confidence Level	Definition
Very high	• Strong evidence (established theory, multiple sources, well-documented and accepted methods, etc.) • High consensus
High	• Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.) • Medium consensus
Medium	• Suggestive evidence (a few sources, limited consistency, 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

Table 2. Calibrated Language for Likelihood Assessment

The calibrated uncertainty terms below are used to express a probabilistic assessment across the evidence base of the likelihood of observed or projected results. Source: Mastrandrea et al. 2011.[4]

Likelihood Assessment	Numeric Probability of Outcome
Virtually certain	99%–100%
Very likely	90%–100%
Likely	66%–100%
As likely as not	33%–66%
Unlikely	0%–33%
Very unlikely	0%–10%
Exceptionally unlikely	0%–1%

Traceable Accounts

Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

Additional information on Key Messages and Traceable Accounts can be found in the Front Matter for NCA4.[2]

Figures and Tables

Each figure in the report includes a figure number and title, a figure intent, and a caption. The figure title (embedded at the top of the figure) briefly describes what is shown in the figure, the figure intent (shown below the figure) provides a key takeaway message of the figure, and the caption (shown below the figure intent) provides additional information on how to interpret the elements of the figure. Where original figures have been developed for the Assessment, the figure credit listed at the end of the caption notes the affiliation of the NCA5 authors or contributors responsible for the development of the figure.

Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation. All figures that appear in the online version of the report are also accompanied by alternative text for screen readers.

Icon	Description
	Share a chapter, chapter section, figure, table, box, or other content element
	Access metadata for a table or figure
	Download a figure
	Access additional information about a figure, table, or box in the Climate Resilience Toolkit
	Access additional information about a figure, table, or box in the NCA5 Atlas

Metrics and Definitions Used Across the Report

Economic Estimates

Unless otherwise noted, economic estimates in this report have been converted to 2022 US dollars using the US Bureau of Economic Analysis's Implicit Price Deflators for Gross Domestic Product, Table 1.1.9.[12] 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 global climate projections for a range of realistic futures. These projections capture variables such as the relationship between human behavior, greenhouse gas (GHG) emissions, the Earth system processes and responses to changes in concentration of GHGs in our atmosphere and oceans, and resulting impacts, including temperature change and sea level rise. Because there are

uncertainties inherent in all of these factors—especially human behavior and the choices that determine emissions levels—the resulting range of projections are not predictions but instead reflect multiple potential pathways for our collective future (Ch. 2). The scenarios do not have relative likelihoods assigned and are all plausible futures.

NCA5 authors were advised to assess the full range of scenarios available. While use of specific scenarios was not mandated across the report, authors were encouraged to report impacts under more than one scenario in order to describe a range of possible outcomes. Few climate projections extend past 2100, limiting the information available for authors to evaluate trends 100 years into the future (Box A3.1).

To help communicate author findings effectively, the naming convention with simplified summary descriptions shown in Table 3 is used across the report to describe the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) used in Phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6), respectively. Scenarios other than those described in Table 3 are referred to by name.

Table 3. Descriptive Terms for Common Climate Scenarios Used in NCA5

This table summarizes the terms used to describe scenarios from Phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6). This standardized terminology is used throughout the report when discussing scenarios to facilitate easier comparison by readers. Sources: Arias et al. 2021; Gidden et al. 2019; Meinshausen et al. 2020; O'Neil et al. 2017; Riahi et al. 2017; van Vuuren et al. 2011 [5,6,7,8,9,10]

Climate Scenario Descriptor	CMIP5	CMIP6	Summary
Very High Scenario	RCP8.5	SSP5-8.5	Among the scenarios described here, these reflect the highest range of carbon dioxide (CO_2) emissions and no mitigation. Total annual global CO_2 emissions in 2100 are quadruple emissions in 2000 (RCP8.5 and SSP5-8.5). Population growth in 2100 doubles from 2000 in RCP8.5, but the SSP5-8.5 population remains relatively stable, with approximately 13% growth in 2100 from 2005. Both scenarios include fossil fuel development, but SSP5-8.5 has higher economic growth than RCP8.5.
High Scenario	RCP6.0	SSP3-7.0	These scenarios reflect high CO_2 emissions with limited (RCP6.0) or no (SSP3-7.0) mitigation. Total annual CO_2 emissions in 2100 are more than 75% higher than in 2000 in RCP6.0, and triple that of 2000 emissions in SSP3-7.0. Compared to 2000, both scenarios include expanded fossil fuel development and population growth but slow economic growth.
Intermediate Scenario	RCP4.5	SSP2-4.5	These scenarios reflect reductions in CO_2 emissions from current levels. Total annual CO_2 emissions in 2100 are 46% (RCP4.5) and 67% (SSP2-4.5) less than the year 2000. Mitigation efforts include low-carbon technology (SSP2-4.5) and expanded renewable energy compared to 2000 (RCP 4.5).
Low Scenario	RCP2.6	SSP1-2.6	These scenarios reflect rapidly declining and net-negative CO_2 emissions (with CO_2 removal from the atmosphere exceeding human-caused emissions) by 2100. Mitigation efforts include increased renewable energy. Adaptive capacity reflects effective governance institutions, reduced inequality, and international cooperation (SSP1-2.6).
Very Low Scenario	n/a	SSP1-1.9	Among the scenarios described here, SSP1-1.9 reflects the greatest reduction in global greenhouse gas emissions and substantial CO_2 removal from the atmosphere. Total annual CO_2 emissions have a steeper decline than SSP1-2.6, dropping by more than 145% by 2100 compared to 2000. Mitigation efforts include a shift to nuclear and renewable energy and sustainable land use. Adaptive capacity benefits from international cooperation and sharing of technology.

Box 1. Global Warming Levels Measure How Much the Planet Has Warmed

In this report, the term "global warming level" is used to describe the level of global temperature increase relative to preindustrial temperatures conditions (the 1850–1900 average). A given global warming level is reached when global annual warming, defined by the average temperature over multiple decades, exceeds a specified level. Although this Assessment primarily reports temperatures in Fahrenheit, global warming levels are usually reported and more widely known in degrees Celsius. For example, the Paris Agreement set a goal of holding the increase in global average temperature to "well below" 2°C (3.6°F) and pursuing efforts to limit the temperature increase to 1.5°C (2.7°F) above preindustrial levels. Thus, global warming levels are typically defined in this report with their Celsius value first and their Fahrenheit value in parentheses.

Internal variability in the climate system means that even as the world rapidly warms, some years will be hotter and some years will be cooler than the multidecadal average. This annual variability means that even if a single year occurs in which Earth is 1.5°C (2.7°F) hotter than the preindustrial average, the 1.5°C global warming level has not necessarily been reached. Conversely, such variability also means that climate impacts projected to occur at a given global warming level may occur earlier than expected, before that level is reached in terms of multidecadal average temperatures. In addition, temperatures in some parts of the world are warmer or cooler than the global average. For example, a global warming level of 2°C (3.6°F) would result in regional temperatures in parts of the United States that are more than 2°C above preindustrial levels (Figure 1.14).

Global warming levels are not thresholds; they do not represent "safe" levels of warming, nor does exceeding a particular global warming level mean that it is too late to slow or halt many of the impacts of climate change by reducing greenhouse gas emissions. Continued action to reduce emissions can avoid the worst impacts of climate change and provide valuable benefits to society and ecosystems no matter what global warming level is reached or exceeded. At regional or local scales, climate impacts, such as increased risks of extreme weather, depend on changes to underlying drivers like local temperatures and rainfall. These changes in turn depend on the level of global warming. The level of global warming depends on future emissions, which depend on human actions. This means that future projections are conditional: when or if Earth reaches a particular level of warming is largely dependent on human choices.

To support decision-making related to future sea level risks, a set of five specific trajectories were selected to cover a range of plausible future global mean sea level conditions. Table 4 displays the naming convention used by NCA5 authors to describe the range of possible rise in global and US sea levels. Although the sea level rise scenarios in Table 4 were developed using global warming levels derived from the Shared Socioeconomic Pathways and there are similarities in the naming conventions (e.g., low, intermediate, high), they have distinct definitions and are used in different ways from the climate scenarios shown in Table 3 (App. 3).[11]

Additional information on scenarios can be found in the Overview and in Appendix 3.

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5

Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022.[11]

Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

Key Advances Since the Fourth National Climate Assessment

Advances since the publication of the Fourth National Climate Assessment (2017–2018) have led to new understanding of the changing climate system, the resulting impacts on society, and approaches to reduce risks. See Appendix 1 for advances in the development process of NCA5.

Physical Climate Science

Reduced uncertainty: New observations combined with improved modeling provide multiple lines of evidence supporting advances in understanding and projections of climate change. Improved understanding has significantly narrowed the estimated range of global warming expected from a doubling of CO_2 in the atmosphere to 4.5°–7.2°F (2.5°–4.0°C). (KMs 3.2, 3.3)

Improved attribution: Advances have increased confidence in the linkages between many weather disasters and climate change, and scientists can now estimate the role of climate change in some types of extreme events in real time. For example, climate change was estimated to have increased the rainfall of Hurricane Harvey in 2017 by about 15% to 20%. (Ch. 2; Introduction; KMs 2.2, 3.3)

Incorporating socioeconomics: New model projections are based on policy-relevant scenarios that span plausible future social and economic development pathways (Table 3). These scenarios allow for a deeper exploration of the interactions between development and emissions pathways, as well as technology pathways to reach net-zero emissions goals. (KMs 2.3, 3.2, 6.3, 32.2; App. 3)

New models: The latest generation of Earth system models incorporates more detailed simulations of the physical climate system and provides improved understanding of how regional-scale processes will change with warming. (KM 3.3)

Risks and Impacts

Connecting justice: More information is available on disproportionate climate change impacts on overburdened communities, including a better understanding of how climate impacts exacerbate, and are exacerbated by, social inequities. (KMs 4.2, 9.2, 11.2, 12.2, 14.3, 15.2, 16.1, 19.1, 21.3, 26.4, 27.1, 31.2; Introductions in Chs. 16, 17, 20)

Untangling interconnections: Observations and enhanced modeling highlight the compounding and cascading effects of climate change on interconnected food, energy, and water systems. Understanding of how climate change affects national security, sustainable and equitable development, and disaster risk reduction and recovery has improved. (Chs. 17, 18; KMs 4.2, 5.2, 6.1, 6.2, 12.2, 19.3)

Damages by degrees: Improved understanding of the risks human and environmental systems face under each additional increment of global warming has helped scientists quantify potential damages to health, ecosystems, livelihoods, and the economy (see Box 1). (Ch. 8, Introduction; KM 19.1)

Responses

Sophisticated support: Improved tools, data, and climate projections needed to support adaptation, mitigation, and resilience measures are becoming more widely available, including advancements in quantifying the economic, health, and environmental benefits from climate actions and better documentation of how the benefits and burdens of investments are distributed. (Ch. 4, Introduction; KMs 5.3, 7.3, 11.3, 12.2, 13.2, 31.5, 32.4; Box 17.1)

Understanding people: The social sciences are providing new insights into how people experience climate change and how climate actions are understood, communicated, and implemented. Increased documentation of institutional changes, partnerships, knowledge sharing, and sustainable financing options are supporting climate action at multiple levels of government. (KMs 12.3, 31.4, 31.6; Ch. 20)

Indigenous Knowledge: Growing efforts to integrate Indigenous Knowledge in community adaptation actions build on accumulated knowledge that has enabled Indigenous Peoples to adapt to environmental change for millennia. (KMs 16.3, 25.5, 27.6, 28.2, 29.5, 30.5; Box 27.2)

Real-world examples: More examples of adaptation in practice, such as green infrastructure, nature-based solutions, and changes in governance and financing, are now available. Cities and states that have implemented adaptation actions are sharing best practices and aiding cooperation, and many communities are learning from climate change responses led by Tribal and Indigenous Peoples. (KMs 12.3, 16.3; Ch. 31)

Reporting Suspected Errata

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Overview: Understanding Risks, Impacts, and Responses



Chapter 1. Overview: Understanding Risks, Impacts, and Responses

Authors and Contributors

Federal Coordinating Lead Author

Allison R. Crimmins, US Global Change Research Program

Chapter Lead Author

Alexa K. Jay, US Global Change Research Program / ICF

Chapter Authors

Christopher W. Avery, US Global Change Research Program / ICF
Travis A. Dahl, US Army Corps of Engineers
Rebecca S. Dodder, US Environmental Protection Agency
Benjamin D. Hamlington, NASA Jet Propulsion Laboratory
Allyza Lustig, US Global Change Research Program / ICF
Kate Marvel, Project Drawdown
Pablo A. Méndez-Lazaro, University of Puerto Rico
Mark S. Osler, National Oceanic and Atmospheric Administration
Adam Terando, US Geological Survey
Emily S. Weeks, US Agency for International Development
Ariela Zycherman, NOAA Climate Program Office

Review Editor

Emily K. Laidlaw, Laidlaw Scientific

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Tammy West

The Fifth National Climate Assessment documents observed and projected vulnerabilities, risks, and impacts associated with climate change across the United States and provides examples of response actions underway in many communities. This Overview presents highlights from the Assessment, providing summary findings and a synthesis of material from the underlying chapters. Curly brackets indicate cross-references to full chapters (e.g., {Ch. 2}), Key Messages (e.g., {2.1}), figures (e.g., {Figure 32.8}), and other text elements.

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Margaret Plumley

How the United States Is Addressing Climate Change

The effects of human-caused climate change are already far-reaching and worsening across every region of the United States. Rapidly reducing greenhouse gas emissions can limit future warming and associated increases in many risks. Across the country, efforts to adapt to climate change and reduce emissions have expanded since 2018, and US emissions have fallen since peaking in 2007. However, without deeper cuts in global net greenhouse gas emissions and accelerated adaptation efforts, severe climate risks to the United States will continue to grow.

Future climate change impacts depend on choices made today

The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases. {2.3, 19.1}

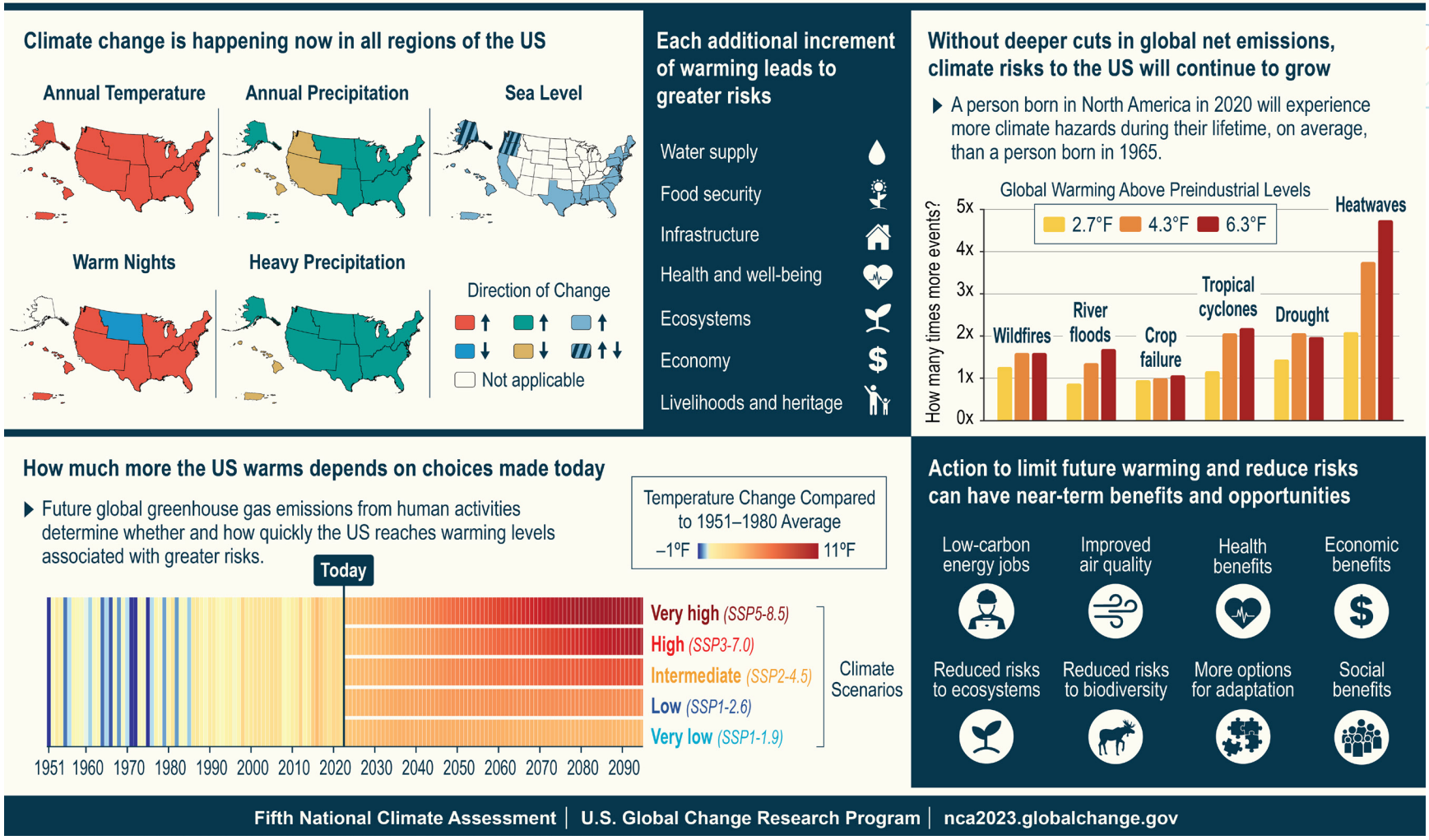
However, this also means that each increment of warming that the world avoids—through actions that cut emissions or remove carbon dioxide (CO_2) from the atmosphere—reduces the risks and harmful impacts of climate change. While there are still uncertainties about how the planet will react to rapid warming, the degree to which climate change will continue to worsen is largely in human hands. {2.3, 3.4}

In addition to reducing risks to future generations, rapid emissions cuts are expected to have immediate health and economic benefits (Figure 1.1). At the national scale, the benefits of deep emissions cuts for current and future generations are expected to far outweigh the costs. {2.1, 2.3, 13.3, 14.5, 15.3, 32.4; Ch. 2, Introduction}



Taelyn B.

Climate Change Risks and Opportunities in the US



Climate change presents risks while action to limit warming and reduce risks presents opportunities for the US.

Figure 1.1. (**top left**) Changes in multiple aspects of climate are apparent in every US region. The five maps present observed changes for five temperature, precipitation, and sea level rise metrics: 1) warming is apparent in every region (based on changes in annual average temperature in 2002–2021 compared to the 1901–1960 average for the contiguous United States, Hawai'i, and Puerto Rico and to 1925–1960 for Alaska); 2) the number of warm nights per year (days with minimum temperatures at or above 70°F in 2002–2021 compared to 1901–1960) is increasing everywhere except the Northern Great Plains, where they have decreased, and in Alaska, where nights above 70°F are not common; 3) average annual precipitation is increasing in most regions, except in the Northwest, Southwest, and Hawai'i, where precipitation has decreased (same time periods as annual average temperature); 4) heavy precipitation events are increasing everywhere except Hawai'i and the US Caribbean, where there has been a decrease (trends over the period 1958–2021); and 5) relative sea levels are increasing along much of the US coast except in Oregon, Washington, and Alaska, where there is a mix of both increases and decreases (trends over 1990–2020). {2.2, 9.1; Figures 2.4, 2.5, 2.7, 2.8}

(**top center**) Every fraction of a degree of additional warming will lead to increasing risks across multiple sectors in the US (see Table 1.2 and "Current and Future Climate Risks to the United States" below). Without rapid, substantial reductions in the greenhouse gases that cause global warming, these climate risks in the US are expected to increase.

(**top right**) People born in North America in 2020, on average, will be exposed to more climate-related hazards compared to people born in 1965. How many more extreme climate events current generations experience compared to previous generations will depend on the level of future warming. {Figure 15.4}

(**bottom left**) This climate stripes chart shows the observed changes in US annual average surface temperature for 1951–2022 and projected changes in temperature for 2023–2095 for five climate scenarios, ranging from a very high scenario, where greenhouse gas emissions continue to increase through most of the century, to a very low scenario, where emissions decline rapidly, reaching net zero by around midcentury (see Figure 1.4 and Table 3 in the Guide to the Report). Each vertical stripe represents the observed or projected change in temperature for a given year compared to the 1951–1980 average; changes are averaged over all 50 states and Puerto Rico but do not include data for the US-Affiliated Pacific Islands and the US Virgin Islands (see also Figure 1.13).

(**bottom right**) Although climate benefits from even the most aggressive emissions cuts may not be detectable before the middle of the century, there are many other potential near-term benefits and opportunities from actions that reduce greenhouse gas emissions. {2.3, 8.3, 10.3, 13.3, 14.5, 15.3, 19.1, 31.3, 32.4}

Figure credits: (top left, top center, top right, bottom right) USGCRP, USGCRP/ICF, NOAA NCEI, and CISESS NC; (bottom left) adapted from panel (c) of Figure SPM.1 in IPCC 2023.

Box 1.1. Mitigation, Adaptation, and Resilience

Throughout this report, three important terms are used to describe the primary options for reducing the risks of climate change:

- **Mitigation**: Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases (primarily carbon dioxide) or removing greenhouse gases from the atmosphere.
- **Adaptation**: The process of adjusting to an actual or expected environmental change and its effects in a way that seeks to moderate harm or exploit beneficial opportunities.
- **Resilience**: The ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions.



James Keul

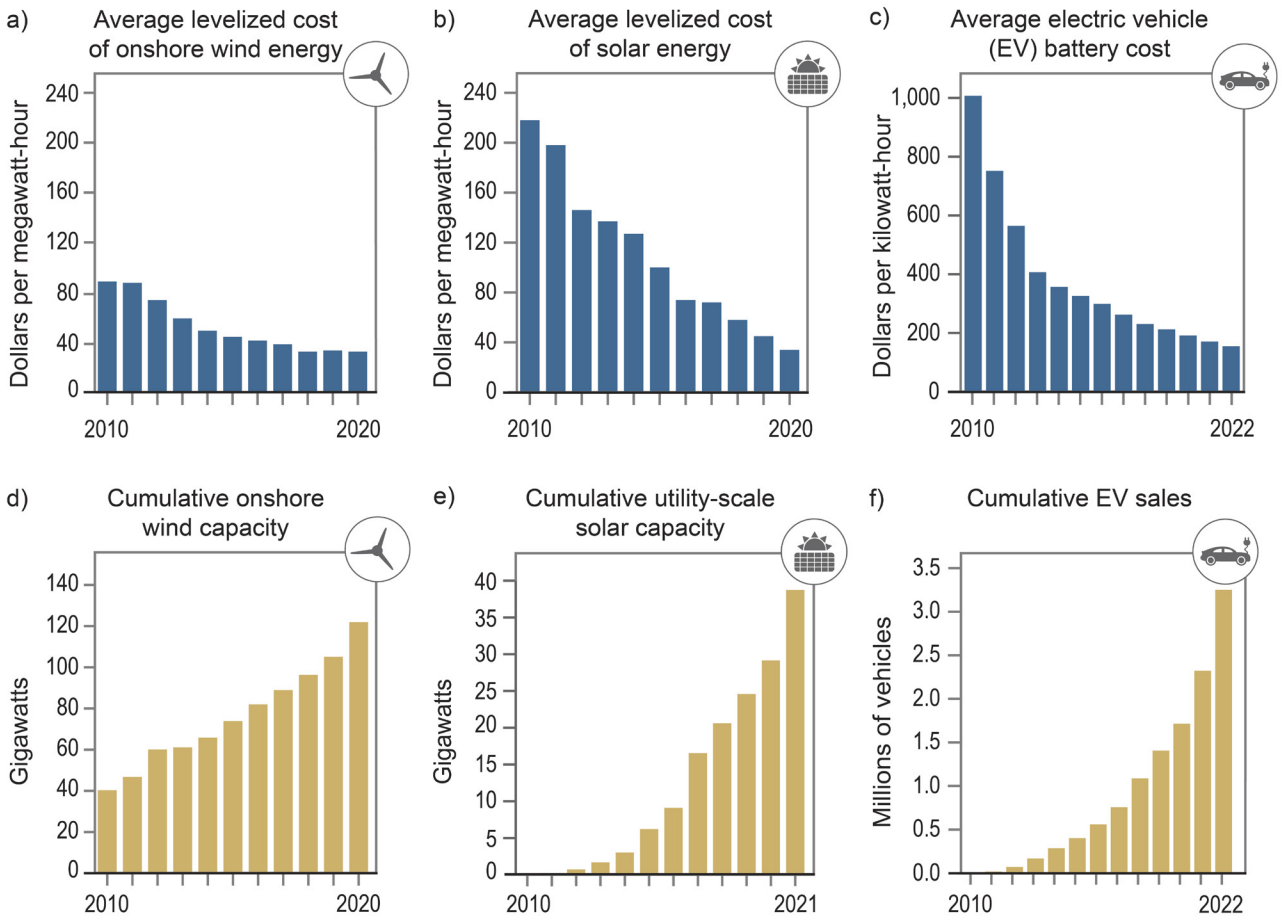
US emissions have decreased, while the economy and population have grown

Annual US greenhouse gas emissions fell 12% between 2005 and 2019. This trend was largely driven by changes in electricity generation: coal use has declined, while the use of natural gas and renewable technologies has increased, leading to a 40% drop in emissions from the electricity sector. Since 2017, the transportation sector has overtaken electricity generation as the largest emitter. {11.1, 13.1, 32.1; Figures 32.1, 32.3}

As US emissions have declined from their peak in 2007, the country has also seen sustained reductions in the amount of energy required for a given quantity of economic activity and the emissions produced per unit of energy consumed. Meanwhile, both population and per capita GDP have continued to grow. {32.1; Figures 32.1, 32.2}

Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources (Figures 1.2, 1.3). {5.3, 12.3, 32.1, 32.2; Figure A4.17}

Across all sectors, innovation is expanding options for reducing energy demand and increasing energy efficiency, moving to zero- and low-carbon electricity and fuels, electrifying energy use in buildings and transportation, and adopting practices that protect and improve natural carbon sinks that remove and store CO_2 from the atmosphere, such as sustainable agricultural and land-management practices. {11.1, 32.2, 32.3; Boxes 32.1, 32.2; Focus on Blue Carbon}



Historical Trends in Unit Costs and Deployment of Low-Carbon Energy Technologies in the United States

Increasing capacities and decreasing costs of low-carbon energy technologies are supporting efforts to further reduce emissions.

Figure 1.2. Costs of onshore wind (**a**), solar photovoltaics (**b**), and electric vehicle (EV) batteries (**c**) have decreased sharply since 2000 (data shown here start in 2010), as the cumulative capacities of wind and solar generation (**d** and **e**) and the cumulative number of EVs sold (**f**) have increased. {Figure 32.8} Figure credit: Electric Power Research Institute, National Renewable Energy Laboratory, NOAA NCEI, and CISESS NC.

Accelerating advances in adaptation can help reduce rising climate risks

As more people face more severe climate impacts, individuals, organizations, companies, communities, and governments are taking advantage of adaptation opportunities that reduce risks. State climate assessments and online climate services portals are providing communities with location- and sector-specific information on climate hazards to support adaptation planning and implementation across the country. New tools, more data, advancements in social and behavioral sciences, and better consideration of practical experiences are facilitating a range of actions (Figure 1.3). {7.3, 12.3, 21.4, 25.4, 31.1, 31.5, 32.5; Table 31.1}

Actions include:

- Implementing nature-based solutions—such as restoring coastal wetlands or oyster reefs—to reduce shoreline erosion {8.3, 9.3, 21.2, 23.5}
- Upgrading stormwater infrastructure to account for heavier rainfall {4.2}
- Applying innovative agricultural practices to manage increasing drought risk {11.1, 22.4, 25.5}
- Assessing climate risks to roads and public transit {13.1}
- Managing vegetation to reduce wildfire risk {5.3}
- Developing urban heat plans to reduce health risks from extreme heat {12.3, 21.1, 28.4}
- Planning relocation from high-risk coastal areas {9.3}

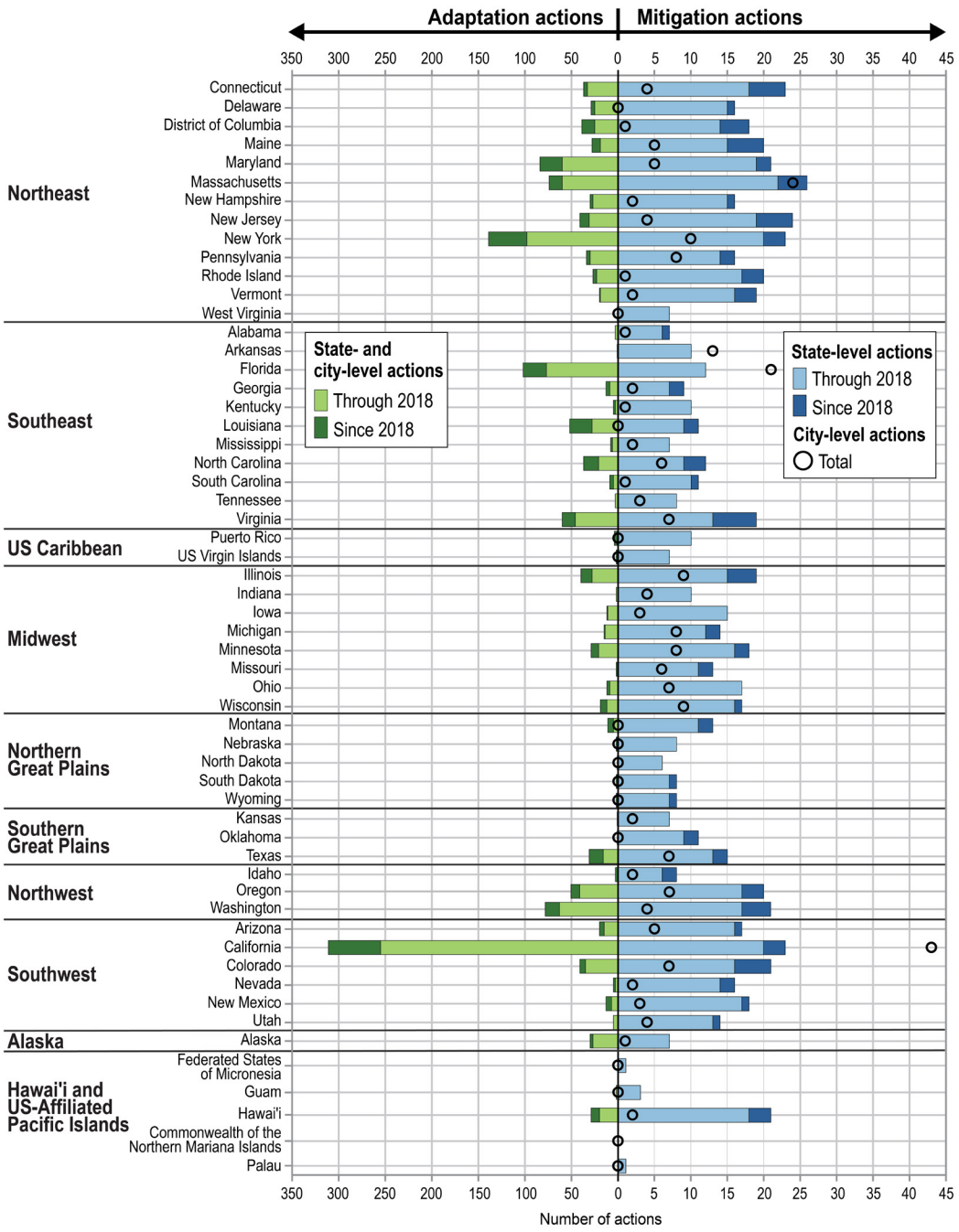
Despite an increase in adaptation actions across the country, current adaptation efforts and investments are insufficient to reduce today's climate-related risks and keep pace with future changes in the climate. Accelerating current efforts and implementing new ones that involve more fundamental shifts in systems and practices can help address current risks and prepare for future impacts (see "Mitigation and adaptation actions can result in systemic, cascading benefits" below). {31.1, 31.3}



Pam DeChellis

Climate action has increased in every region of the US

Efforts to adapt to climate change and reduce net greenhouse gas emissions are underway in every US region and have expanded since 2018 (Figure 1.3; Table 1.1). Many actions can achieve both adaptation and mitigation goals. For example, improved forest- or land-management strategies can both increase carbon storage and protect ecosystems, and expanding renewable energy options can reduce emissions while also improving resilience. {31.1, 32.5}



US Adaptation and Mitigation Actions

Cities and states are acting on climate change, with a substantial increase in new activities underway since 2018.

Figure 1.3. Since 2018, city- and state-level adaptation plans and actions (**green bars**, left) increased by 32%, complemented by a 14% increase in the total number of new state-level mitigation activities (**blue bars**, right; 69% have updated their policies). In 2021 there were 271 city-level mitigation actions in place (**open circles**, right), according to the Global Climate Action Tracker. Renewable energy and energy efficiency projects on Tribal lands have also expanded (not shown). {31.1, 32.5; Figure 16.4; Table 1.1} Figure credit: US Army Corps of Engineers, EPA, Pennsylvania State University, NOAA NCEI, and CISESS-NC.

Climate adaptation and mitigation efforts involve trade-offs, as climate actions that benefit some or even most people can result in burdens to others. To date, some communities have prioritized equitable and inclusive planning processes that consider the social impacts of these trade-offs and help ensure that affected communities can participate in decision-making. As additional measures are implemented, more widespread consideration of their social impact can help inform decisions around how to distribute the outcomes of investments. {12.4, 13.4, 20.2, 21.3, 21.4, 26.4, 27.1, 31.2, 32.4, 32.5; Box 20.1}

Table 1.1. Climate Actions Are Taking Place Across All US Regions

Examples of recent local adaptation, resilience, and mitigation actions around the country follow.

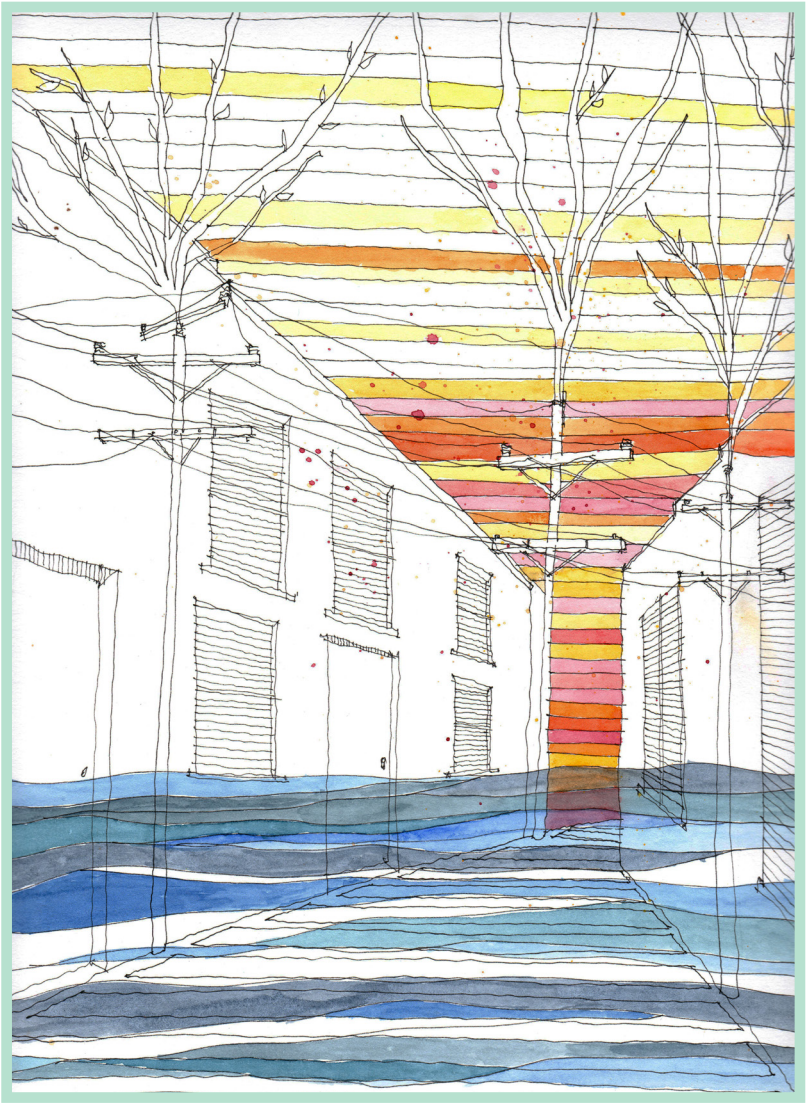
Region	Action
Northeast	The 2022 stormwater code in Pittsburgh, Pennsylvania, requires new developments to plan for projected increases in heavy rainfall under climate change rather than building to historical rainfall amounts. In 2021, the city also committed to achieve carbon neutrality by 2050. {Box 21.1}
Southeast	Following repeated flooding from multiple hurricanes, measures to reduce flood risk in Princeville, North Carolina, include buyouts, elevating homes, and building housing that meets local flood standards. In Orlando, Florida, the city and businesses are adopting commercial building energy-efficiency requirements and electric vehicle readiness policies and have used wastewater and food scraps from parks and resorts to generate renewable biogas. {Boxes 22.1, 32.3}
US Caribbean	Many community-based organizations in Puerto Rico have undertaken actions to advance adaptation, social transformation, and sustainable development. These organizations work to expand renewable energy and equitable access to energy resources, prepare for disasters, restore ecosystems, strengthen agriculture and food security, and protect public health. {23.5}
Midwest	A wetland creation project in Ashtabula, Ohio, restored habitat displaced by shoreline development, improving coastal protection for the port on Lake Erie. In Michigan, some state forestlands are being managed to bolster carbon storage and to support recreation and wildlife habitat. {24.2, 24.4; Figure 24.9}
Northern Great Plains	The Nebraska Natural Resources Conservation Service supported farmers in testing soil health and evaluating soil management practices that promote climate adaptation. Across the region, wind electricity generation tripled between 2011 and 2021, with a growing number of Tribes leading the Nation's renewable energy transition by installing wind, solar, and hydropower. {25.3, 25.5; Box 25.3}
Southern Great Plains	Texas- and Kansas-based groups are supporting soil and land management practices that increase carbon storage while protecting important ecosystems. Wind and solar energy generation and battery storage capacities have also grown, with the region accounting for 42% of national wind-generated electricity in 2022. {26.2}
Northwest	The Confederated Tribes of the Colville Reservation are prioritizing carbon capture in their forest and timber management efforts, leading to improved air and water quality and wildlife habitat as well as preservation of cultural areas and practices. {27.3}
Southwest	In response to severe drought, seven Colorado River basin states, the US and Mexican governments, and Indigenous Peoples are collaborating to improve water conservation and develop adaptation solutions. Dozens of cities are committed to emissions reductions; for instance, Phoenix is on track to meet a 2030 goal of 50% reduction in greenhouse gas emissions from 2018 levels. {Ch. 28, Introduction; Box 28.1}
Alaska	To address climate threats to traditional foods, the Chugach Regional Resources Commission is integrating Indigenous Knowledge and Western scientific methods in its adaptation efforts, including weekly water sampling for harmful algal blooms and restoring clam populations. Kelp farming is also being developed to reduce the effects of ocean acidification, serve as a carbon sink, and generate income. {29.7; Box 29.7}
Hawai'i and US-Affiliated Pacific Islands	The Kaua'i Island Utility Cooperative achieved a 69.5% renewable portfolio standard in 2021, and the island is occasionally 100% renewably powered during midday hours; it is projected to achieve a 90% renewable portfolio by 2026. Guam, the Republic of the Marshall Islands, the Federated States of Micronesia, and Palau plan to use blue carbon ecosystems to offset emissions while also protecting coastal infrastructure. {30.3; Box 30.3}

Meeting US mitigation targets means reaching net-zero emissions

The global warming observed over the industrial era is unequivocally caused by greenhouse gas emissions from human activities—primarily burning fossil fuels. Atmospheric concentrations of carbon dioxide (CO_2)—the primary greenhouse gas produced by human activities—and other greenhouse gases continue to rise due to ongoing global emissions. Stopping global warming would require both reducing emissions of CO_2 to net zero and rapid and deep reductions in other greenhouse gases. Net-zero CO_2 emissions means that CO_2 emissions decline to zero or that any residual emissions are balanced by removal from the atmosphere. {2.3, 3.1; Ch. 32}

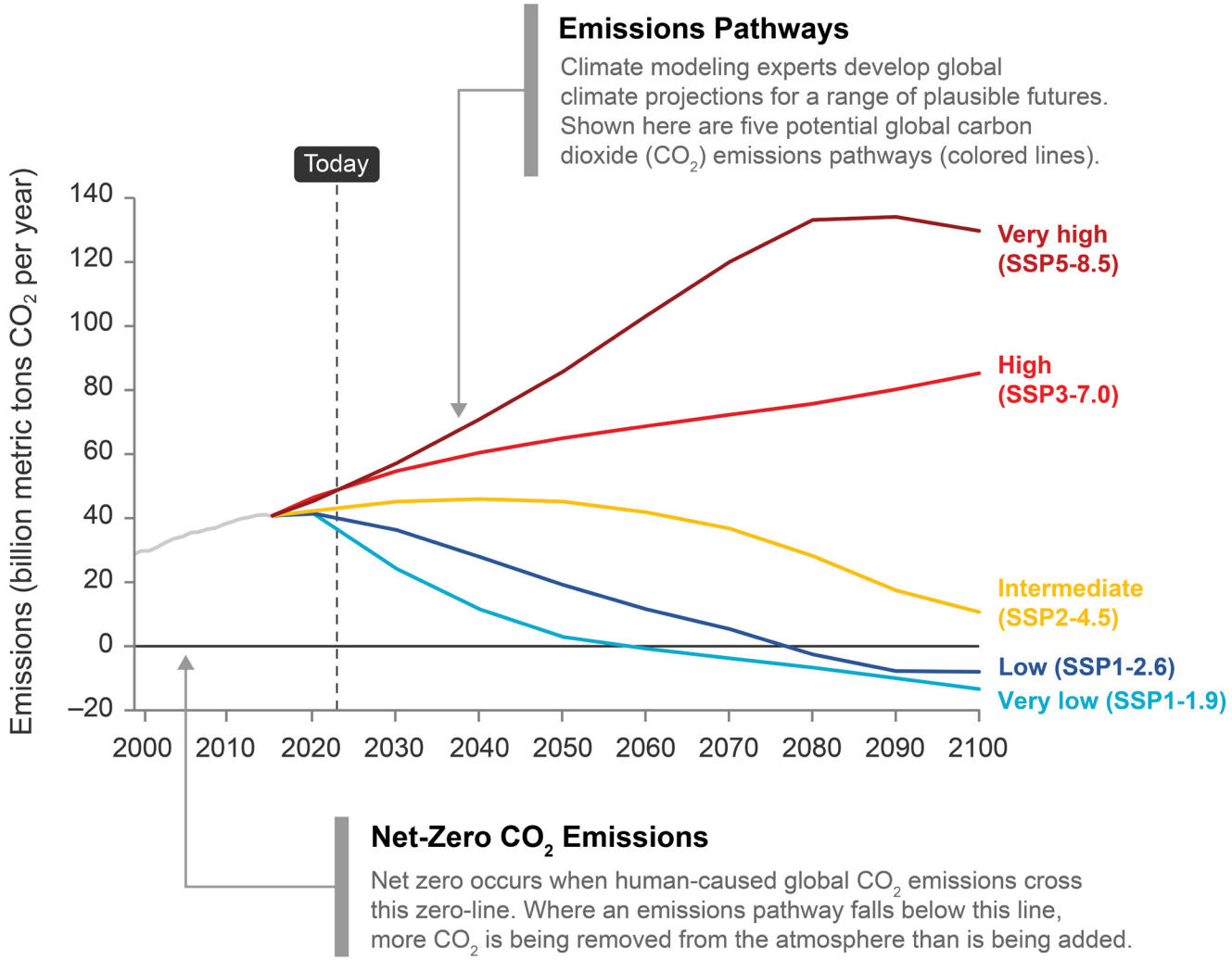
Once CO_2 emissions reach net zero, the global warming driven by CO_2 is expected to stop: additional warming over the next few centuries is not necessarily "locked in" after net CO_2 emissions fall to zero. However, global average temperatures are not expected to fall for centuries unless CO_2 emissions become net negative, which is when CO_2 removal from the atmosphere exceeds CO_2 emissions from human activities. Regardless of when or if further warming is avoided, some long-term responses to the temperature changes that have already occurred will continue. These responses include sea level rise, ice sheet losses, and associated disruptions to human health, social systems, and ecosystems. In addition, the ocean will continue to acidify after the world reaches net-zero CO_2 emissions, as it continues to gradually absorb CO_2 in the atmosphere from past emissions. {2.1, 2.3, 3.1; Ch. 2, Introduction}

National and international commitments seek to limit global warming to well below 2°C (3.6°F), and preferably to 1.5°C (2.7°F), compared to preindustrial temperature conditions (defined as the 1850–1900 average). To achieve this, global CO_2 emissions would have to reach net zero by around 2050 (Figure 1.4); global emissions of all greenhouse gases would then have to reach net zero within the following few decades. {2.3, 32.1}



Andrea Ruedy Trimble

Future Global Carbon Dioxide Emissions Pathways



Different scenarios of future carbon dioxide emissions are used to explore the range of possible climate futures.

Figure 1.4. The five scenarios shown (colored lines) demonstrate potential global carbon dioxide (CO_2) emissions pathways modeled from 2015 through 2100, with the solid light gray line showing observed global CO_2 emissions from 2000 to 2015. See Table 3 in the Guide to the Report for scenario definitions. Many projected impacts described in this report are based on a potential climate future defined by one or more of these scenarios for future CO_2 emissions from human activities, the largest long-term driver of climate change. The vertical dashed line, labeled "Today," marks the year 2023; the solid horizontal black line marks net-zero CO_2 emissions. Adapted with permission from Figure TS.4 in Arias et al. 2021.

While US greenhouse gas emissions are falling, the current rate of decline is not sufficient to meet national and international climate commitments and goals. US net greenhouse gas emissions remain substantial and would have to decline by more than 6% per year on average, reaching net-zero emissions around midcentury, to meet current national mitigation targets and international temperature goals; by comparison, US greenhouse gas emissions decreased by less than 1% per year on average between 2005 and 2019. {32.1}

Many cost-effective options that are feasible now have the potential to substantially reduce emissions over the next decade. Faster and more widespread deployment of renewable energy and other zero- and low-carbon energy options can accelerate the transition to a decarbonized economy and increase the chances of meeting a 2050 national net-zero greenhouse gas emissions target for the US. However, to reach the US net-zero emissions target, additional mitigation options need to be explored and advanced (see "Available mitigation strategies can deliver substantial emissions reductions, but additional options are needed to reach net zero" below). {5.3, 6.3, 32.2, 32.3}



David Zeiset

How the United States Is Experiencing Climate Change

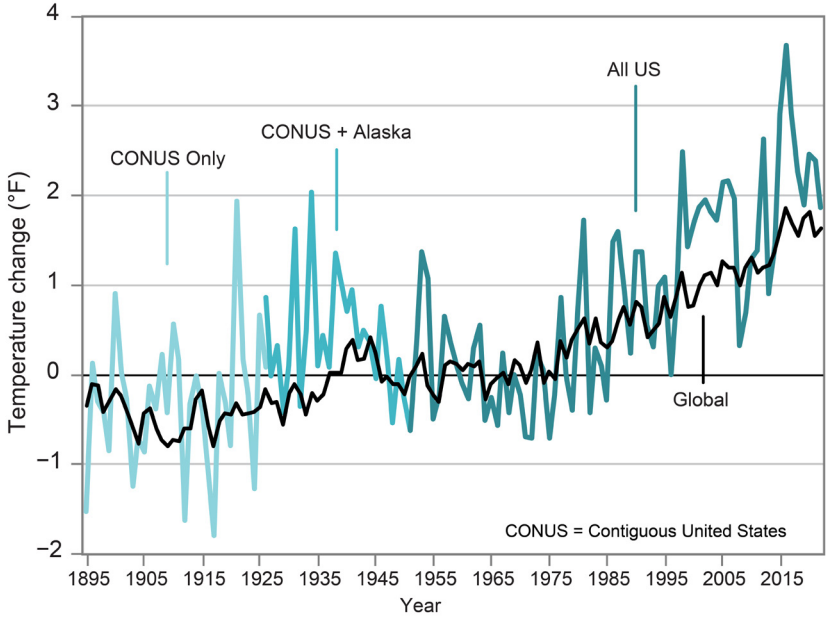
As extreme events and other climate hazards intensify, harmful impacts on people across the United States are increasing. Climate impacts—combined with other stressors—are leading to ripple effects across sectors and regions that multiply harms, with disproportionate effects on underserved and overburdened communities.

Current climate changes are unprecedented over thousands of years

Global greenhouse gas emissions from human activities continue to increase, resulting in rapid warming (Figure 1.5) and other large-scale changes, including rising sea levels, melting ice, ocean warming and acidification, changing rainfall patterns, and shifts in timing of seasonal events. Many of the climate conditions and impacts people are experiencing today are unprecedented for thousands of years (Figure 1.6). {2.1, 3.1; Figures A4.6, A4.7, A4.10, A4.13}

As the world's climate has shifted toward warmer conditions, the frequency and intensity of extreme cold events have declined over much of the US, while the frequency, intensity, and duration of extreme heat have increased. Across all regions of the US, people are experiencing warming temperatures and longer-lasting heatwaves. Over much of the country, nighttime temperatures and winter temperatures have warmed more rapidly than daytime and summer temperatures. Many other extremes, including heavy precipitation, drought, flooding, wildfire, and hurricanes, are becoming more frequent and/or severe, with a cascade of effects in every part of the country. {2.1, 2.2, 3.4, 4.1, 4.2, 7.1, 9.1; Ch. 2, Introduction; App. 4; Focus on Compound Events}

US and Global Changes in Average Surface Temperature



The US has warmed rapidly since the 1970s.

Figure 1.5. The graph shows the change in US annual average surface temperature during 1895–2022 compared to the 1951–1980 average. The temperature trend changes color as data become available for more regions of the US, with Alaska data added to the average temperature for the contiguous US (CONUS) beginning in 1926 (medium blue line) and Hawai'i, Puerto Rico, and US-Affiliated Pacific Islands data added beginning in 1951 (dark blue line). Global average surface temperature is shown by the black line. Figure credit: NOAA NCEI and CISESS NC.

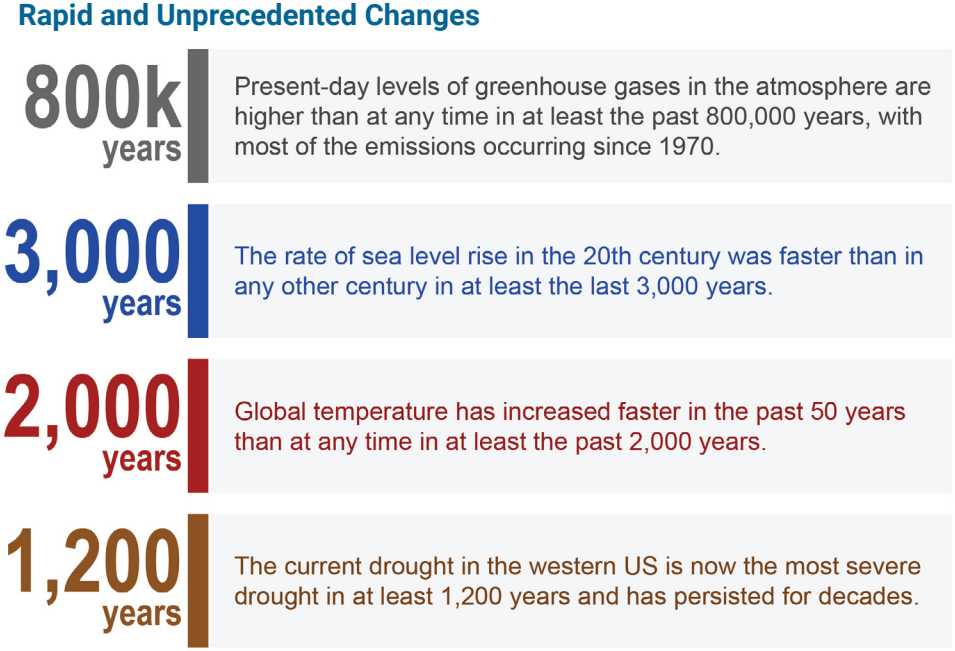


Figure 1.6. Human activities since industrialization have led to increases in atmospheric greenhouse gas concentrations that are unprecedented in records spanning hundreds of thousands of years. These are examples of some of the large and rapid changes in the climate system that are occurring as the planet warms. (Greenhouse gas concentrations {2.1}; sea level rise {3.4}; global temperature {2.1}; drought {2.2, 3.5}) Figure credit: USGCRP and ICF.

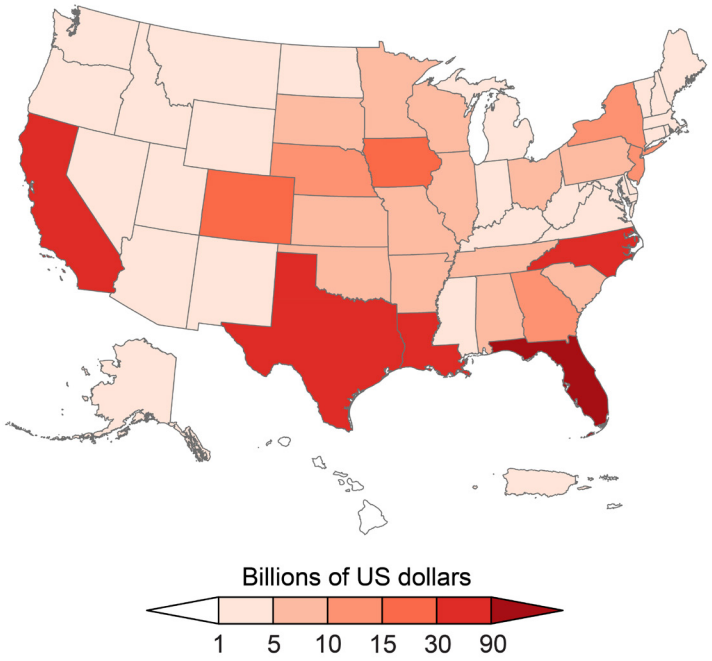
Risks from extreme events are increasing

One of the most direct ways that people experience climate change is through changes in extreme events. Harmful impacts from more frequent and severe extremes are increasing across the country—including increases in heat-related illnesses and death, costlier storm damages, longer droughts that reduce agricultural productivity and strain water systems, and larger, more severe wildfires that threaten homes and degrade air quality. {2.2, 4.2, 12.2, 14.2, 15.1, 19.2; Focus on Western Wildfires}

Extreme weather events cause direct economic losses through infrastructure damage, disruptions in labor and public services, and losses in property values. The number and cost of weather-related disasters have increased dramatically over the past four decades, in part due to the increasing frequency and intensity of extreme events and in part due to increases in assets at risk (through population growth, rising property values, and continued development in hazard-prone areas). Low-income communities, communities of color, and Tribes and Indigenous Peoples experience high exposure and vulnerability to extreme events due to both their proximity to hazard-prone areas and lack of adequate infrastructure or disaster management resources. {2.2, 4.2, 17.3, 19.1; Focus on Compound Events}

In the 1980s, the country experienced, on average, one (inflation-adjusted) billion-dollar disaster every four months. Now, there is one every three weeks, on average. Between 2018 and 2022, the US experienced 89 billion-dollar events (Figure 1.7). Extreme events cost the US close to $150 billion each year—a conservative estimate that does not account for loss of life, healthcare-related costs, or damages to ecosystem services. {2.2, 19.1; Ch. 2, Introduction; Figures 4.1, A4.5}

Damages by State from Billion-Dollar Disasters (2018–2022)



The US now experiences, on average, a billion-dollar weather or climate disaster every three weeks.

Figure 1.7. Billion-dollar weather and climate disasters are events where damages/costs reach or exceed $1 billion, including adjustments for inflation. Between 2018 and 2022, 89 such events affected the US, including 4 droughts, 6 floods, 52 severe storms, 18 tropical cyclones, 5 wildfires, and 4 winter storm events (see Figure A4.5 for the number of billion-dollar disasters per year). During this period, Florida had the highest total damages ($140 billion) and experienced the highest damages from a single event—Hurricane Ian ($113 billion). Over the 1980–2022 period, Texas had the highest total damages ($375 billion). While similar data are not available for the US-Affiliated Pacific Islands, Super Typhoon Yutu caused $500 million in property damage alone in Saipan and the northern Marianas in 2018 (NCEI 2019). Increasing costs over time are driven by changes in the assets at risk and the increase in frequency or intensity of extreme events caused by climate change. Adapted from NCEI 2023.

Cascading and compounding impacts increase risks

The impacts and risks of climate change unfold across interacting sectors and regions. For example, wildfire in one region can affect air quality and human health in other regions, depending on where winds transport smoke. Further, climate change impacts interact with other stressors, such as the COVID-19 pandemic, environmental degradation, or socioeconomic stressors like poverty and lack of adequate housing that disproportionately impact overburdened communities. These interactions and interdependencies can lead to cascading impacts and sudden failures. For example, climate-related shocks to the food supply chain have led to local to global impacts on food security and human migration patterns that affect US economic and national security interests. {11.3, 17.1, 17.2, 17.3, 18.1, 22.3, 23.4, 31.3; Introductions in Chs. 2, 17, 18; Focus on Compound Events; Focus on Risks to Supply Chains; Focus on COVID-19 and Climate Change}

The risk of two or more extreme events occurring simultaneously or in quick succession in the same region—known as compound events—is increasing. Climate change is also increasing the risk of multiple extremes occurring simultaneously in different locations that are connected by complex human and natural systems. For instance, simultaneous megafires across multiple western states and record back-to-back Atlantic hurricanes in 2020 caused unprecedented demand on federal emergency response resources. {2.2, 3.2, 15.1, 22.2, 26.4; Focus on Compound Events; Ch. 4, Introduction}

Compound events often have cascading impacts that cause greater harm than individual events. For example, in 2020, record-breaking heat and widespread drought contributed to concurrent destructive wildfires across California, Oregon, and Washington, exposing millions to health hazards and straining firefighting resources. Ongoing drought amplified the record-breaking Pacific Northwest heatwave of June 2021, which

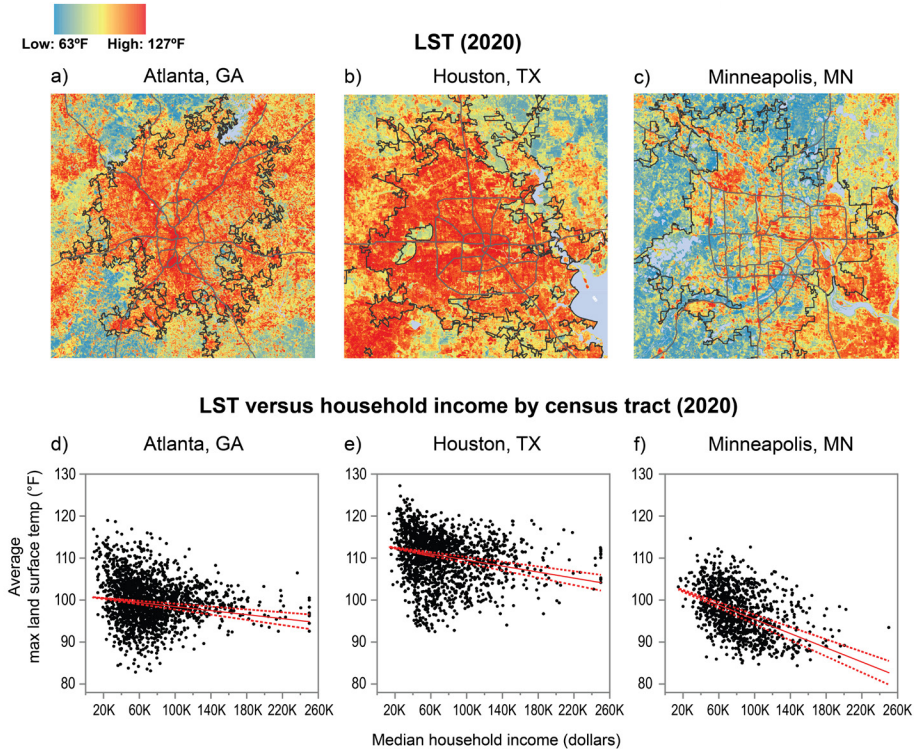
was made 2° to 4°F hotter by climate change. The heatwave led to more than 1,400 heat-related deaths, another severe wildfire season, mass die-offs of fishery species important to the region's economy and Indigenous communities, and total damages exceeding $38.5 billion (in 2022 dollars). {27.3; Ch. 2, Introduction; Focus on Compound Events, Focus on Western Wildfires}

Climate change exacerbates inequities

Some communities are at higher risk of negative impacts from climate change due to social and economic inequities caused by ongoing systemic discrimination, exclusion, and under- or disinvestment. Many such communities are also already overburdened by the cumulative effects of adverse environmental, health, economic, or social conditions. Climate change worsens these long-standing inequities, contributing to persistent disparities in the resources needed to prepare for, respond to, and recover from climate impacts. {4.2, 9.2, 12.2, 14.3, 15.2, 16.1, 16.2, 18.2, 19.1, 20.1, 20.3, 21.3, 22.1, 23.1, 26.4, 27.1, 31.2}

For example, low-income communities and communities of color often lack access to adequate flood infrastructure, green spaces, safe housing, and other resources that help protect people from climate impacts. In some areas, patterns of urban growth have led to the displacement of under-resourced communities to suburban and rural areas with less access to climate-ready housing and infrastructure. Extreme heat can lead to higher rates of illness and death in low-income neighborhoods, which are hotter on average (Figure 1.8). Neighborhoods that are home to racial minorities and low-income people have the highest inland (riverine) flood exposures in the South, and Black communities nationwide are expected to bear a disproportionate share of future flood damages—both coastal and inland (Figure 1.9). {4.2, 11.3, 12.2, 15.1, 22.1, 22.2, 26.4, 27.1; Ch. 2, Introduction}

Land Surface Temperature and Its Relationship to Median Household Income for Three Cities

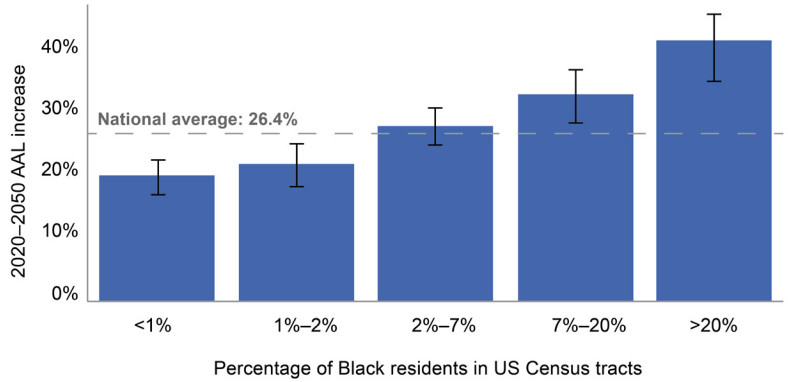


Lower-income urban neighborhoods experience higher surface temperatures.

Figure 1.8. The figure shows the spatial distribution of maximum land surface temperature (LST) in 2020 for Atlanta (**a**), Houston (**b**), and Minneapolis (**c**). Graphs (**d**), (**e**), and (**f**) depict the relationship between maximum LST and median household income across census tracts in each city (see also Figure A4.4). A statistical trend analysis (the Theil-Sen estimator) returns negative values for all three cities, indicating that LST decreases as income increases (solid red line). Dashed red lines indicate the 95% confidence interval, meaning that the true slope of the trend is expected to fall within this range. Note that LST is measured at ground level and may differ from surface air temperature, which is measured at a height of 2 meters. {Figure 12.6} Portions of this figure include intellectual property of Esri and its licensors and are used under license. Copyright © 2020 Esri and its licensors. All rights reserved. Figure credit: University of California, Davis; University of Texas at El Paso; Massachusetts Institute of Technology; City of Phoenix, Arizona; and USGS.

These disproportionate impacts are partly due to exclusionary housing practices—both past and ongoing—that leave underserved communities with less access to heat and flood risk-reduction strategies and other economic, health, and social resources. For example, areas that were historically redlined—a practice in which lenders avoided providing services to communities, often based on their racial or ethnic makeup—continue to be deprived of equitable access to environmental amenities like urban green spaces that reduce exposure to climate impacts. These neighborhoods can be as much as 12°F hotter during a heatwave than nearby wealthier neighborhoods. {8.3, 9.2, 12.2, 15.2, 20.3, 21.3, 22.1, 26.4, 27.1, 32.4; Ch. 2, Introduction}

Projected Increases in Average Annual Losses (AALs) from Floods by 2050



Losses due to floods are projected to increase disproportionately in US Census tracts with higher percentages of Black residents.

Figure 1.9. The bars show that the average annual losses—or the economic damage in a typical year—due to floods in census tracts with a Black population of at least 20% are projected to increase at roughly twice the rate of that in tracts where Black populations make up less than 1% of population. {Figure 4.14} Adapted from Wing et al. 2022 [CC BY 4.0].

Harmful impacts will increase in the near term

Even if greenhouse gas emissions fall substantially, the impacts of climate change will continue to intensify over the next decade (see "Meeting US mitigation targets means reaching net-zero emissions" above; Box 1.4), and all US regions are already experiencing increasingly harmful impacts. Although a few US regions or sectors may experience limited or short-term benefits from climate change, adverse impacts already far outweigh any positive effects and will increasingly eclipse benefits with additional warming. {2.3, 19.1; Ch. 2, Introduction; Chs. 21–30}

Table 1.2 shows examples of critical impacts expected to affect people in each region between now and 2030, with disproportionate effects on overburdened communities. While these examples affect particular regions in the near term, impacts often cascade through social and ecological systems and across borders and may lead to longer-term losses. {15.2, 18.2, 20.1; Figure 15.5; Ch. 20, Introduction}

Table 1.2. Climate Change Is Already Affecting All US Regions and Will Continue to Have Impacts in the Near Term

The table shows three climate impacts of significant concern to each US region between now and 2030. Icons indicate general categories of impacts: infrastructure, water supply, health and well-being, food security, economy, livelihoods and heritage, and ecosystems. More information can be found in the regional chapters (Chs. 21–30).

Infrastructure | Water Supply | Health and Well-Being | Food Security | Economy | Livelihoods and Heritage | Ecosystems

Northeast

- Extreme weather events damage critical infrastructure. {21.1}
- Warming temperatures shift distributions of coastal and marine species and habitats. {21.2}
- Extreme heat and flooding disproportionately impact overburdened communities. {21.3}

Southeast

- Sea level rise and coastal flooding harm rapidly growing communities. {22.1}
- Extreme heat threatens human health, especially stressing urban communities. {22.2}
- Heavy rain and longer dry spells reduce water supply and access. {22.4}

US Caribbean

- Agricultural losses, especially from tropical cyclones, threaten food security. {23.1}
- Severe drought leads to large agricultural and economic losses. {23.3}
- Rising temperatures increase mortality and power demand; hurricanes and storms stress power grids. {23.2, 23.4}

Midwest

- Rising temperatures and extreme events threaten livelihoods and trades. {24.2}
- Extreme weather events harm public health. {24.3}
- Rising temperatures and extreme rainfall damage buildings, homes, and businesses. {24.4}

Northern Great Plains

- Rising temperatures and decreasing snowpack reduce water supply. {25.1}
- Increases in extreme heat, wildfire, and flooding harm physical and mental health. {25.1, 25.2}
- Livelihoods are at greater risk, especially in agriculture, recreation, and energy sectors. {25.3}

Southern Great Plains

- Drier conditions threaten agriculture, ecosystems, and water supplies. {26.1, 26.2, 26.5}
- Extreme heat and high humidity harm human health and exacerbate inequities. {26.4}
- Multiple stressors and extreme events disrupt business, outdoor recreation, and leisure activities. {26.1, 26.2, 26.3}

Northwest



Less water is available for hydropower, rural communities, and aquatic ecosystems. {27.1, 27.2, 27.4}



Extreme heat and wildfire smoke endanger at-risk urban, rural, and Tribal communities. {27.1, 27.3, 27.5}



Wildfire, extreme heat, and floods threaten livelihoods and heritage tied to natural resources. {27.1, 27.3, 27.6}

Alaska



Landscape degradation increases damage to private and municipal infrastructure. {29.2, 29.4}



Reduced fish stocks harm local economies, Tribal sovereignty, and overall well-being. {29.6, 29.7}



Diminished access to mammals, seabirds, fish, and vegetation decreases local food security. {29.5}

Southwest



Intensifying drought and decreases in groundwater recharge reduce water supply. {28.1}



Economic losses to farmers and ranchers increase. {28.3}



Extreme heat, drought, wildfire smoke, and coastal flooding harm physical and mental health. {28.3, 28.4}

Hawai‘i and US-Affiliated Pacific Islands



Sea level rise and saltwater intrusion reduce irrigation and drinking water supply. {30.1}



Damages to the coastal built environment, including traditional structures, increase. {30.3, 30.5}



Risks to unique and biodiverse flora and fauna continue to grow. {30.4}

Current and Future Climate Risks to the United States

Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities. Many of the extreme events and harmful impacts that people are already experiencing will worsen as warming increases and new risks emerge.

Safe, reliable water supplies are threatened by flooding, drought, and sea level rise

More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. Urban and agricultural environments are especially vulnerable to runoff and flooding. Between 1981 and 2016, US corn yield losses from flooding were comparable to those from extreme drought. Runoff and flooding also transport debris and contaminants that cause harmful algal blooms and pollute drinking water supplies. Communities of color and low-income communities face disproportionate flood risks. {2.2, 4.2, 6.1, 9.2, 21.3, 24.1, 24.5, 26.4; Figure A4.8}

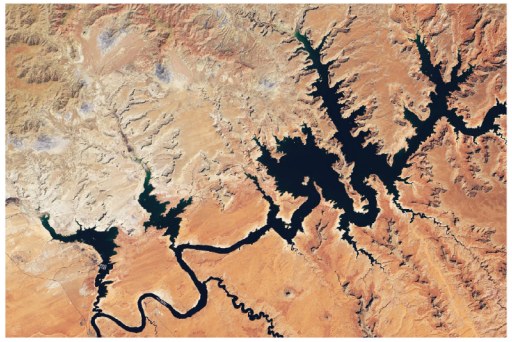
Between 1980 and 2022, drought and related heatwaves caused approximately $328 billion in damages (in 2022 dollars). Recent droughts have strained surface water and groundwater supplies, reduced agricultural productivity, and lowered water levels in major reservoirs, threatening hydropower generation. As higher temperatures increase irrigation demand, increased pumping could endanger groundwater supplies, which are already declining in many major aquifers. {4.1, 4.2; Figure A4.9}

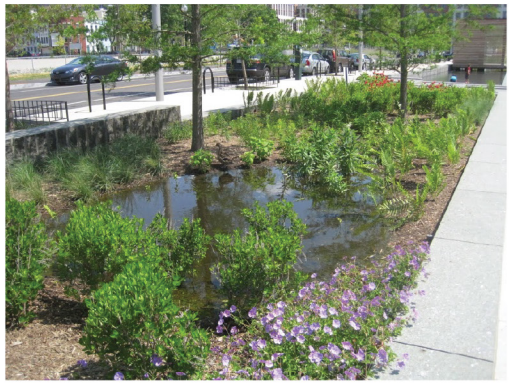
Droughts are projected to increase in intensity, duration, and frequency, especially in the Southwest, with implications for surface water and groundwater supplies. Human and natural systems are threatened by rapid shifts between wet and dry periods that make water resources difficult to predict and manage. {2.2, 2.3, 4.1, 4.2, 5.1, 28.1}

In coastal environments, dry conditions, sea level rise, and saltwater intrusion endanger groundwater aquifers and stress aquatic ecosystems. Inland, decreasing snowpack alters the volume and timing of streamflow and increases wildfire risk. Small rural water providers that often depend on a single water source or have limited capacity are especially vulnerable. {4.2, 7.2, 9.2, 21.2, 22.1, 23.1, 23.3, 25.1, 27.4, 28.1, 28.2, 28.5, 30.1; Figure A4.7}

Many options are available to protect water supplies, including reservoir optimization, nature-based solutions, and municipal management systems to conserve and reuse water. Collaboration on flood hazard management at regional scales is particularly important in areas where flood risk is increasing, as cooperation can provide solutions unavailable at local scales. {4.3, 9.3, 26.5; Focus on Blue Carbon}







(**left**; Toledo, Ohio) Rising temperatures are intensifying harmful algal blooms, negatively affecting human and animal health. (**top right**; Utah, Arizona) Water levels on Lake Powell have fallen to historic lows in recent years, affecting millions of people across the Southwest. (**bottom right**) Rain gardens, a form of green infrastructure, absorb excess stormwater. Photo credits: (left) Aerial Associates Photography Inc. by Zachary Haslick; (top right) NASA Earth Observatory images by Lauren Dauphin, using Landsat data from the USGS; (bottom right) Alisha Goldstein, EPA.

Disruptions to food systems are expected to increase

As the climate changes, increased instabilities in US and global food production and distribution systems are projected to make food less available and more expensive. These price increases and disruptions are expected to disproportionately affect the nutrition and health of women, children, older adults, and low-wealth communities. {11.2, 15.2}

Climate change also disproportionately harms the livelihoods and health of communities that depend on agriculture, fishing, and subsistence lifestyles, including Indigenous Peoples reliant on traditional food sources. Heat-related stress and death are significantly greater for farmworkers than for all US civilian workers. {11.2, 11.3, 15.1, 15.2, 16.1; Focus on Risks to Supply Chains}

While farmers, ranchers, and fishers have always faced unpredictable weather, climate change heightens risks in many ways:

- Increasing temperatures, along with changes in precipitation, reduce productivity, yield, and nutritional content of many crops. These changes can introduce disease, disrupt pollination, and result in crop failure, outweighing potential benefits of longer growing seasons and increased CO_2 fertilization. {11.1, 19.1, 21.1, 22.4, 23.3, 24.1, 26.2}
- Heavy rain and more frequent storms damage crops and property and contaminate water supplies. Longer-lasting droughts and larger wildfires reduce forage production and nutritional quality, diminish water supplies, and increase heat stress on livestock. {23.2, 25.3, 28.3}
- Increasing water temperatures, invasive aquatic species, harmful algal blooms, and ocean acidification and deoxygenation put fisheries at risk. Fishery collapses can result in large economic losses, as well as loss of cultural identity and ways of life. {11.3, 29.3}

In response, some farmers and ranchers are adopting innovations—such as agroecological practices, data-driven precision agriculture, and carbon monitoring—to improve resilience, enhance soil carbon storage, and reduce emissions. Across the Nation, Indigenous food security efforts are helping improve community resilience to climate change while also improving cultural resilience. Some types of aquaculture have the potential to increase climate-smart protein production, human nutrition, and food security, although some communities have raised concerns over issues such as conflict with traditional livelihoods and the introduction of disease or pollution. {10.2, 11.1, 29.6, 25.5; Boxes 22.3, 27.2}







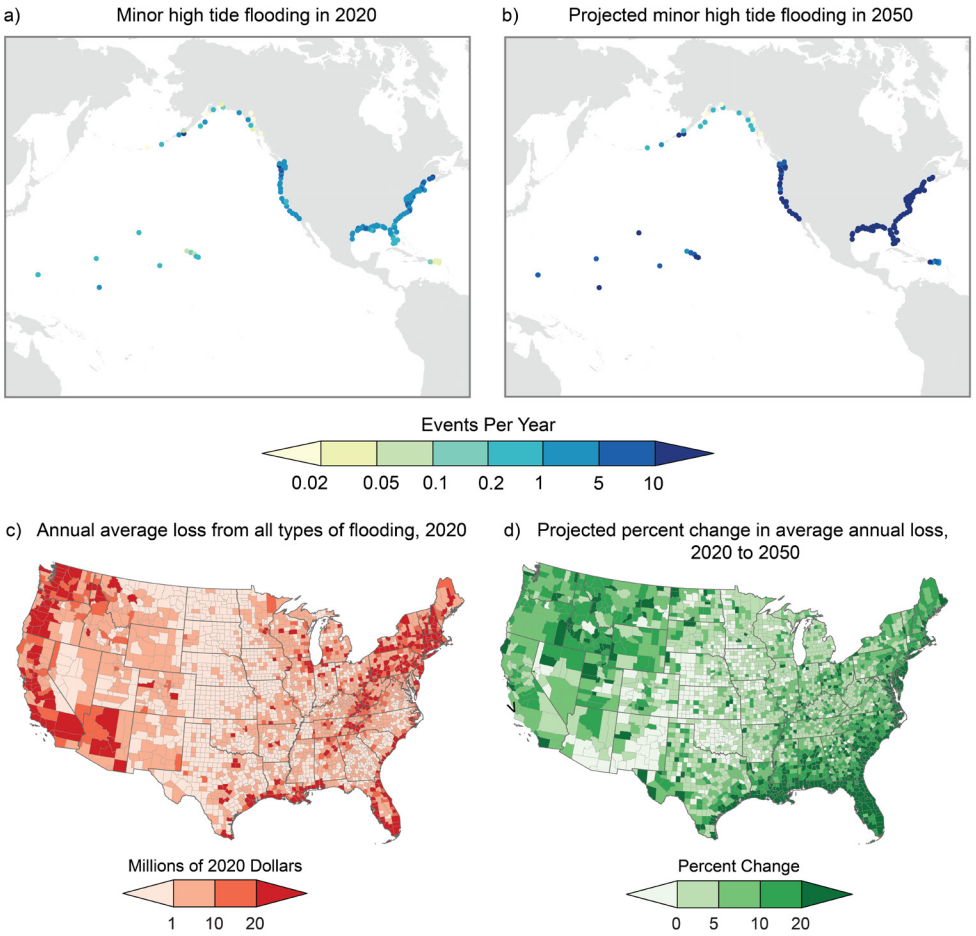
(**left**; Baltimore, Maryland) Urban farms offer the potential to reduce carbon emissions while helping to improve community food security. (**top right**; California) A Northern California vineyard is affected by wildfire. (**bottom right**; Kenai River, Alaska) Recent climate extremes have contributed to declines in many salmon populations. Photo credits: (left) Preston Keres, USDA/FPAC; (top right) Ordinary Mario/iStock via Getty Images; (bottom right) Eric Vance, EPA.

Homes and property are at risk from sea level rise and more intense extreme events

Homes, property, and critical infrastructure are increasingly exposed to more frequent and intense extreme events, increasing the cost of maintaining a safe and healthy place to live. Development in fire-prone areas and increases in area burned by wildfires have heightened risks of loss of life and property damage in many areas across the US. Coastal communities across the country—home to 123 million people (40% of the total US population)—are exposed to sea level rise (Figure 1.10), with millions of people at risk of being displaced from their homes by the end of the century. {2.3, 9.1, 12.2, 22.1, 27.4, 30.3; Figures A4.10, A4.14; Focus on Western Wildfires}

People who regularly struggle to afford energy bills—such as rural, low-income, and older fixed-income households and communities of color—are especially vulnerable to more intense extreme heat events and associated health risks, particularly if they live in homes with poor insulation and inefficient cooling systems. For example, Black Americans are more likely to live in older, less energy efficient homes and face disproportionate heat-related health risks. {5.2, 15.2, 15.3, 22.2, 26.4, 32.4; Figure A4.4}

Accessible public cooling centers can help protect people who lack adequate air-conditioning on hot days. Strategic land-use planning in cities, urban greenery, climate-smart building codes, and early warning communication can also help neighborhoods adapt. However, other options at the household scale, such as hardening homes against weather extremes or relocation, may be out of reach for renters and low-income households without assistance. {12.3, 15.3, 19.3, 22.2}



US Flooding Risks in 2020 and 2050

Increasing flooding puts more people and assets at risk.

Figure 1.10. (**top row**) Maps show (**a**) the average number of minor high tide flooding events per year in 2020 (with historical sea level rise) and (**b**) the expected number of events per year in 2050 (when driven by extrapolated sea level rise). (**bottom row**) Maps show (**c**) average annual loss (AAL) from all types of flooding in millions of dollars in 2020 and (**d**) the projected changes in AAL in 2050 relative to 2020. AAL estimates were made only for the contiguous US. Over the next three decades, the number of flooding days along all coastlines of the US is expected to increase. These increases in the occurrence of flooding will drive greater AALs, especially in coastal areas of the US. (a, b) Adapted from Sweet et al. 2022; (c, d) adapted from Wing et al. 2022 [CC BY 4.0].

Box 1.2. Migration and Displacement

Extreme events, such as extended drought, wildfire, and major hurricanes, have contributed to human migration and displacement. For example, numerous extreme events over the last two decades drove migration of vulnerable communities in Puerto Rico and the US Virgin Islands to the mainland. {9.2, 15.1, 17.2, 19.2, 23.1, 23.5; Box 18.2}

In the future, the combination of climate change and other factors, such as housing affordability, is expected to increasingly affect migration patterns. More severe wildfires in California, increasing sea level rise in Florida, and more frequent flooding in Texas are expected to displace millions of people. Climate-driven economic changes abroad, including reductions in crop yields, are expected to increase the rate of emigration to the United States. {9.2, 17.2, 19.2, 30.3}

From Alaska to low-lying Pacific atolls, forced migrations and displacements driven by climate change disrupt social networks, decrease housing security, and exacerbate grief, anxiety, and negative mental health outcomes. Indigenous Peoples, who have long faced land dispossession due to settler colonialism, are again being confronted with displacement and loss of traditional resources and practices. {4.2, 15.1, 16.1, 19.1, 20.1, 20.3, 22.1, 22.2, 29.1, 30.3; Box 18.2}





(**left**; Cedar Rapids, Iowa) More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. (**right**; Arizona) The 2021 Telegraph Fire destroyed homes and property. Photo credits: (left) Don Becker, USGS; (right) Andrew Avitt, USDA Forest Service.

Infrastructure and services are increasingly damaged and disrupted by extreme weather and sea level rise

Climate change threatens vital infrastructure that moves people and goods, powers homes and businesses, and delivers public services. Many infrastructure systems across the country are at the end of their intended useful life and are not designed to cope with additional stress from climate change. For example, extreme heat causes railways to buckle, severe storms overload drainage systems, and wildfires result in roadway obstruction and debris flows. Risks to energy, water, healthcare, transportation, telecommunications, and waste management systems will continue to rise with further climate change, with many infrastructure systems at risk of failing. {12.2, 13.1, 15.2, 23.4, 26.5; Focus on Risks to Supply Chains}

In coastal areas, sea level rise threatens permanent inundation of infrastructure, including roadways, railways, ports, tunnels, and bridges; water treatment facilities and power plants; and hospitals, schools, and military bases. More intense storms also disrupt critical services like access to medical care, as seen after Hurricanes Irma and Maria in the US Virgin Islands and Puerto Rico. {9.2, 23.1, 28.2, 30.3}

At the same time, climate change is expected to place multiple demands on infrastructure and public services. For example, higher temperatures and other effects of climate change, such as greater exposure to stormwater or wastewater, will increase demand for healthcare. Continued increases in average temperatures and more intense heatwaves will heighten electricity and water demand, while wetter storms and intensified

hurricanes will strain wastewater and stormwater management systems. In the Midwest and other regions, aging energy grids are expected to be strained by disruptions and transmission efficiency losses from climate change. {23.4, 24.4, 30.2}

Forward-looking designs of infrastructure and services can help build resilience to climate change, offset costs from future damage to transportation and electrical systems, and provide other benefits, including meeting evolving standards to protect public health, safety, and welfare. Mitigation and adaptation activities are advancing from planning stages to deployment in many areas, including improved grid design and workforce training for electrification, building upgrades, and land-use choices. Grid managers are gaining experience planning and operating electricity systems with growing shares of renewable generation and working toward understanding the best approaches for dealing with the natural variability of wind and solar sources alongside increases in electrification. {5.3, 12.3, 13.1, 13.2, 22.3, 24.4, 32.3; Figure 22.17}

Climate change exacerbates existing health challenges and creates new ones

Climate change is already harming human health across the US, and impacts are expected to worsen with continued warming. Climate change harms individuals and communities by exposing them to a range of compounding health hazards, including the following:

- More severe and frequent extreme events {2.2, 2.3, 15.1}
- Wider distribution of infectious and vector-borne pathogens {15.1, 26.1; Figure A4.16}
- Air quality worsened by smog, wildfire smoke, dust, and increased pollen {14.1, 14.2, 14.4, 23.1, 26.1}
- Threats to food and water security {11.2, 15.1}
- Mental and spiritual health stressors {15.1}





(**left**; Oregon) The Hooskanaden Landslide, triggered by heavy rainfall, caused substantial road damage. (**right**; Maunabo, Puerto Rico) Punta Tuna Wetlands Nature Reserve, which helps buffer the coastline from extreme events, was severely damaged during Hurricane Maria in 2017. Photo credits: (left) Oregon Department of Transportation [CC BY 2.0]; (right) Kenneth Wilsey, FEMA.

While climate change can harm everyone's health, its impacts exacerbate long-standing disparities that result in inequitable health outcomes for historically marginalized people, including people of color, Indigenous Peoples, low-income communities, and sexual and gender minorities, as well as older adults, people with disabilities or chronic diseases, outdoor workers, and children. {14.3, 15.2}

The disproportionate health impacts of climate change compound with similar disparities in other health contexts. For example, climate-related disasters during the COVID-19 pandemic, such as drought along the Colorado River basin, western wildfires, and Hurricane Laura, disproportionately magnified COVID-19 exposure, transmission, and disease severity and contributed to worsened health conditions for essential workers, older adults, farmworkers, low-wealth communities, and communities of color. {15.2; Focus on COVID-19 and Climate Change}

Large reductions in greenhouse gas emissions are expected to result in widespread health benefits and avoided death or illness that far outweigh the costs of mitigation actions. Improving early warning, surveillance, and communication of health threats; strengthening the resilience of healthcare systems; and supporting community-driven adaptation strategies can reduce inequities in the resources and capabilities needed to adapt as health threats from climate change continue to grow. {14.5, 15.3, 26.1, 30.2, 32.4}



(**left**; New York, New York) The Empire State Building is shrouded in a haze caused by smoke from the 2023 Canadian wildfires. (top right; Charleston, South Carolina) An ambulance drives through floodwaters. (bottom right; Atlanta, Georgia) Heatwaves in the Southeast are happening more frequently. Park amenities, such as trees and splash pads, help cool people on hot days. Photo credits: (left) Anthony Quintano [CC BY 2.0]; (top right) US Air National Guard photo by Tech. Sgt. Jorge Intriago; (bottom right) ucumari photography [CC BY-NC-ND 2.0]

Box 1.3. Indigenous Ways of Life and Spiritual Health

Indigenous communities, whose ways of life, cultures, intergenerational continuity, and spiritual health are tied to nature and the environment, are experiencing disproportionate health impacts of climate change. Rising temperatures and intensifying extreme events are reducing biodiversity and shifting the ranges of culturally important species like Pacific salmon, wild rice, and moose, making it more difficult for Indigenous Peoples to fish, hunt, and gather traditional and subsistence resources within Tribal jurisdictions. Heatwaves can prevent Tribal members from participating in traditional ceremonies, while flooding, erosion, landslides, and wildfires increasingly disrupt or damage burial grounds and ceremonial sites. {16.1, 15.2, 27.6}

Indigenous Peoples are leading numerous actions in response to climate change, including planning and policy initiatives, youth movements, cross-community collaborative efforts, and the expansion of renewable energy (Figure 1.11). Many of these efforts involve planning processes that start with place-based Indigenous Knowledge of local climate and ecosystems. {16.3}

Exemplifying Indigenous Resilience



Figure 1.11. For over 2,000 years, the Hopi People have farmed on land with only 6–10 inches of annual precipitation. Today, Hopi children learn both the practices and process of Hopi dryland farming and the values, customs, and identities that underpin them. Photo credit: ©Michael K. Johnson. {Panel from Figure 16.6}

Ecosystems are undergoing transformational changes

Together with other stressors, climate change is harming the health and resilience of ecosystems, leading to reductions in biodiversity and ecosystem services. Increasing temperatures continue to shift habitat ranges as species expand into new regions or disappear from unfavorable areas, altering where people can hunt, catch, or gather economically important and traditional food sources. Degradation and extinction of local flora and fauna in vulnerable ecosystems like coral reefs and montane rainforests are expected in the near term, especially where climate changes favor invasive species or increase susceptibility to pests and pathogens. Without significant emissions reductions, rapid shifts in environmental conditions are expected to lead to irreversible ecological transformations by mid- to late century. {2.3, 6.2, 7.1, 7.2, 8.1, 8.2, 10.1, 10.2, 21.1, 24.2, 27.2, 28.5, 29.3, 29.5, 30.4; Figure A4.12}







Changes in ocean conditions and extreme events are already transforming coastal, aquatic, and marine ecosystems. Coral reefs are being lost due to warming and ocean acidification, harming important fisheries; coastal forests are converting to ghost forests, shrublands, and marsh due to sea level rise, reducing coastal protection; lake and stream habitats are being degraded by warming, heavy rainfall, and invasive species, leading to declines in economically important species. {8.1. 10.1, 21.2, 23.2, 24.2, 27.2; Figures 8.7, A4.11}

Increased risks to ecosystems are expected with further climate change and other environmental changes, such as habitat fragmentation, pollution, and overfishing. For example, mass fish die-offs from extreme summertime heat are projected to double by midcentury in northern temperate lakes under a very high scenario (RCP8.5). Continued climate changes are projected to exacerbate runoff and erosion, promote harmful algal blooms, and expand the range of invasive species. {4.2, 7.1, 8.2, 10.1, 21.2, 23.2, 24.2, 27.2, 28.2, 30.4}

While adaptation options to protect fragile ecosystems may be limited, particularly under higher levels of warming, management and restoration measures can reduce stress on ecological systems and build resilience. These measures include migration assistance for vulnerable species and protection of essential habitats, such as establishing wildlife corridors or places where species can avoid heat. Opportunities for nature-based solutions that assist in mitigation exist across the US, particularly those focused on protecting existing carbon sinks and increasing carbon storage by natural ecosystems. {8.3, 10.3, 23.2, 27.2; Focus on Blue Carbon}

(**top left**; Nags Head Woods, North Carolina) Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion. (**top right**; Molokai Island, Hawai'i) High island ecosystems are at risk due to invasive species, habitat destruction, intensifying fire, and drought. (**bottom**; Florida) A diver works on coral reef restoration around Florida Keys National Marine Sanctuary. Photo credits: (top left) NC Wetlands [CC BY 2.0]; (top right) Lucas Fortini, USGS; (bottom) Mitchell Tartt, NOAA.

Climate change slows economic growth, while climate action presents opportunities

With every additional increment of global warming, costly damages are expected to accelerate. For example, 2°F of warming is projected to cause more than twice the economic harm induced by 1°F of warming. Damages from additional warming pose significant risks to the US economy at multiple scales and can compound to dampen economic growth. {19.1}

- International impacts can disrupt trade, amplify costs along global supply chains, and affect domestic markets. {17.3, 19.2; Focus on Risks to Supply Chains}
- While some economic impacts of climate change are already being felt across the country, the impacts of future changes are projected to be more significant and apparent across the US economy. {19.1}
- States, cities, and municipalities confront climate-driven pressures on public budgets and borrowing costs amid spending increases on healthcare and disaster relief. {19.2}
- Household consumers face higher costs for goods and services, like groceries and health insurance premiums, as prices change to reflect both current and projected climate-related damages. {19.2}

Mitigation and adaptation actions present economic opportunities. Public and private measures—such as climate financial risk disclosures, carbon offset credit markets, and investments in green bonds—can avoid economic losses and improve property values, resilience, and equity. However, climate responses are not without risk. As innovation and trade open further investment opportunities in renewable energy and the country continues to transition away from fossil fuels, loss and disposal costs of stranded capital assets such as coal mines, oil and gas wells, and outdated power plants are expected. Climate solutions designed without input from affected communities can also result in increased vulnerability and cost burden. {17.3, 19.2, 19.3, 20.2, 20.3, 27.1, 31.6}

Many regional economies and livelihoods are threatened by damages to natural resources and intensifying extremes

Climate change is projected to reduce US economic output and labor productivity across many sectors, with effects differing based on local climate and the industries unique to each region. Climate-driven damages to local economies especially disrupt heritage industries (e.g., fishing traditions, trades passed down over generations, and cultural heritage–based tourism) and communities whose livelihoods depend on natural resources. {11.3, 19.1, 19.3}

- As fish stocks in the Northeast move northward and to deeper waters in response to rapidly rising ocean temperatures, important fisheries like scallops, shrimp, and cod are at risk. In Alaska, climate change has already played a role in 18 major fishery disasters that were especially damaging for coastal Indigenous Peoples, subsistence fishers, and rural communities. {10.2, 21.2, 29.3}
- While the Southeast and US Caribbean face high costs from projected labor losses and heat health risks to outdoor workers, small businesses are already confronting higher costs of goods and services and potential closures as they struggle to recover from the effects of compounding extreme weather events. {22.3, 23.1}
- Agricultural losses in the Midwest, including lower corn yields and damages to specialty crops like apples, are linked to rapid shifts between wet and dry conditions and stresses from climate-induced increases in pests and pathogens. Extreme heat and more intense wildfire and drought in the Southwest are already threatening agricultural worker health, reducing cattle production, and damaging wineries. {24.1, 28.5}
- In the Northern Great Plains, agriculture and recreation are expected to see primarily negative effects related to changing temperature and rainfall patterns. By 2070, the

Southern Great Plains is expected to lose cropland acreage as lands transition to pasture or grassland. {25.3, 26.2}

- Outdoor-dependent industries, such as tourism in Hawai'i and the US-Affiliated Pacific Islands and skiing in the Northwest, face significant economic loss from projected rises in park closures and reductions in workforce as continued warming leads to deterioration of coastal ecosystems and shorter winter seasons with less snowfall. {7.2, 8.3, 10.1, 10.3, 19.1, 27.3, 30.4}

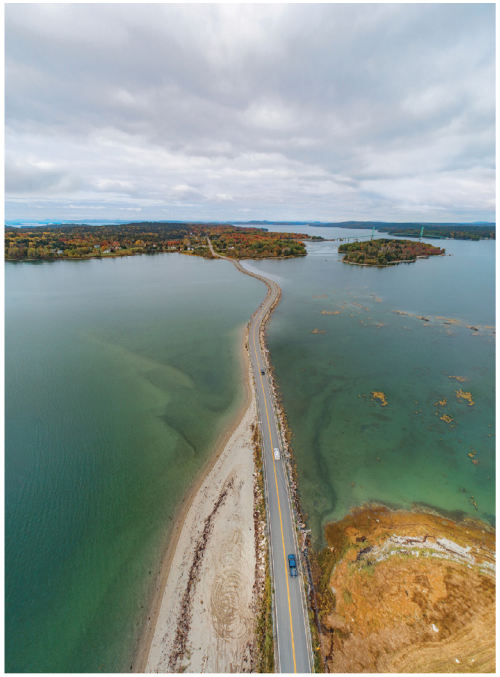
Mitigation and adaptation actions taken by businesses and industries promote resilience and offer long-term benefits to employers, employees, and surrounding communities. For example, as commercial fisheries adapt, diversifying harvest and livelihoods can help stabilize income or buffer risk. In addition, regulators and investors are increasingly requiring businesses to disclose climate risks and management strategies. {10.2, 19.3, 26.2}



Scarlett W.







(**top left**; Fort Myers Beach, Florida) Shops and restaurants were severely damaged or completed destroyed by Hurricane Ian in 2022. (**bottom left**; Whatcom County, Washington) Snow-based recreational industries, such as skiing in the Pacific Northwest, are projected to lose revenue due to declining snowpack. (**right**; Maine) A causeway connecting Little Deer Isle to Deer Isle (the largest lobster port in the state) is threatened by sea level rise. Photo credits: (top left) Coast Guard Petty Officer 3rd Class Gabriel Wisdom; (bottom left) US Forest Service–Pacific Northwest Region; (right) ©Jack Sullivan, Island Institute.

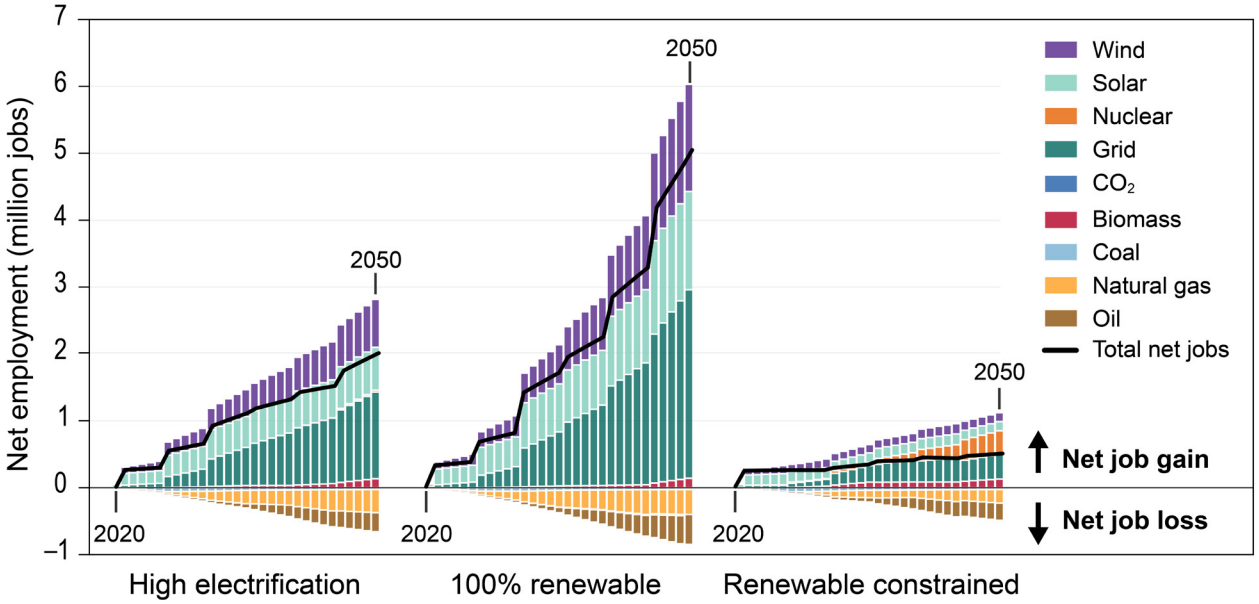
Job opportunities are shifting due to climate change and climate action

Many US households are already feeling the economic impacts of climate change. Climate change is projected to impose a variety of new or higher costs on most households as healthcare, food, insurance, building, and repair costs become more expensive. Compounding climate stressors can increase segregation, income inequality, and reliance on social safety net programs. Quality of life is also threatened by climate change

in ways that can be more difficult to quantify, such as increased crime and domestic violence, harm to mental health, reduced happiness, and fewer opportunities for outdoor recreation and play. {11.3, 19.1, 19.3}

Climate change, and how the country responds, is expected to alter demand for workers and shift where jobs are available. For example, energy-related livelihoods in the Northern and Southern Great Plains are expected to shift as the energy sector transforms toward more renewables, low-carbon technologies, and electrification of more sectors of the economy. Losses in fossil fuel–related jobs are projected to be completely offset by greater increases in mitigation-related jobs, as increased demand for renewable energy and low-carbon technologies is expected to lead to long-term expansion in most states' energy and decarbonization workforce (Figure 1.12). Grid expansion and energy efficiency efforts are already creating new jobs in places like Nevada, Vermont, and Alaska, and advancements in biofuels and agrivoltaics (combined renewable energy and agriculture) provide economic opportunities in rural communities. {10.2, 11.3, 19.3, 25.3, 26.2, 29.3, 32.4}

Additional opportunities include jobs in ecosystem restoration and construction of energy-efficient and climate-resilient housing and infrastructure. Workforce training and equitable access to clean energy jobs, which have tended to exclude women and people of color, are essential elements of a just transition to a decarbonized economy. {5.3, 19.3, 20.3, 22.3, 25.3, 26.2, 27.3, 32.4}



Energy Employment (2020–2050) for Alternative Net-Zero Pathways

Employment gains in electrification and renewable energy industries are projected to far outpace job losses in fossil fuel industries.

Figure 1.12. Despite decreases in the number of fossil fuel–related jobs, the overall number of energy jobs (specifically those involved in the supply of energy) relative to 2019 is generally projected to increase in net-zero-emissions energy scenarios between 2020 and 2050, although by much more in some scenarios than in others. {Figure 32.17} Adapted with permission from Jenkins et al. 2021.







(**top**; Golden, Colorado) Solar panels are pictured on the campus of the National Renewable Energy Laboratory. (**bottom left**; San Antonio, Texas) Participants in the 2022 Collegiate Wind Competition focus on offshore wind projects. (**bottom right**; Lexington, Virginia) Workers install fiber-optic cables. Rural broadband deployment is associated with higher incomes and lower unemployment rates. Photo credits: (top and bottom left) Werner Slocum/NREL [CC-BY-NC-ND 2.0]; (bottom right) Preston Keres, USDA

Climate change is disrupting cultures, heritages, and traditions

As climate change transforms US landscapes and ecosystems, many deeply rooted community ties, pastimes, Traditional Knowledges, and cultural or spiritual connections to place are at risk. Cultural heritage—including buildings, monuments, livelihoods, and practices—is threatened by impacts on natural ecosystems and the built environment. Damages to archaeological, cultural, and historical sites further reduce opportunities to transfer important knowledge and identity to future generations. {6.1, 7.2, 8.3, 9.2, 10.1, 12.2, 16.1, 22.1, 23.1, 26.1, 27.6, 28.2; Introductions in Chs. 10, 30}

Many outdoor activities and traditions are already being affected by climate change, with overall impacts projected to further hinder recreation, cultural practices, and the ability of communities to maintain local heritage and a sense of place. {19.1}

For example:

- The prevalence of invasive species and harmful algal blooms is increasing as waters warm, threatening activities like swimming along Southeast beaches, boating and fishing for walleye in the Great Lakes, and viewing whooping cranes along the Gulf Coast. In the Northwest, water-based recreation demand is expected to increase in spring and summer months, but reduced water quality and harmful algal blooms are expected to restrict these opportunities. {24.2, 24.5, 26.3, 27.6}

- Ranges of culturally important species are shifting as temperatures warm, making them harder to find in areas where Indigenous Peoples have access (see Box 1.3). {11.2, 24.2, 26.1}
- Hikers, campers, athletes, and spectators face increasing threats from more severe heatwaves, wildfires, and floods and greater exposure to infectious disease. {15.1, 22.2, 26.3, 27.6}

Nature-based solutions and ecosystem restoration can preserve cultural heritage while also providing valuable local benefits, such as flood protection and new recreational opportunities. Cultural heritage can also play a key role in climate solutions, as incorporating local values, Indigenous Knowledge, and equity into design and planning can help reaffirm a community's connection to place, strengthen social networks, and build new traditions. {7.3, 26.1, 26.3, 30.5}



(**top left**; Glacier National Park, Montana) Wildfire smoke jeopardizes participation in outdoor sports and recreation. (**top right**; Boston Harbor, Massachusetts) Sea level rise threatens historical and archaeological sites on the Boston Harbor Islands. (**bottom**; Goose Island, Texas) Whooping cranes, which draw birdwatchers to the Gulf of Mexico, are at risk due to flooding, drought, and upstream water use. Photo credit: (top left) Andrew Parlette [CC BY 2.0]; (top right) cmh2315fl [CC BY-NC 2.0]; (bottom) Alan Schmierer [CC0 1.0].

The Choices That Will Determine the Future

With each additional increment of warming, the consequences of climate change increase. The faster and further the world cuts greenhouse gas emissions, the more future warming will be avoided, increasing the chances of limiting or avoiding harmful impacts to current and future generations.

Societal choices drive greenhouse gas emissions

The choices people make on a day-to-day basis—how to power homes and businesses, get around, and produce and use food and other goods—collectively determine the amount of greenhouse gases emitted. Human use of fossil fuels for transportation and energy generation, along with activities like manufacturing and agriculture, has increased atmospheric levels of carbon dioxide (CO_2) and other heat-trapping greenhouse gases. Since 1850, CO_2 concentrations have increased by almost 50%, methane by more than 156%, and nitrous oxide by 23%, resulting in long-term global warming. {2.1, 3.1; Ch. 2, Introduction}

The CO_2 not removed from the atmosphere by natural sinks lingers for thousands of years. This means that CO_2 emitted long ago continues to contribute to climate change today. Because of historical trends, cumulative CO_2 emissions from fossil fuels and industry in the US are higher than from any other country. To understand the total contributions of past actions to observed climate change, additional warming from CO_2 emissions from land use, land-use change, and forestry, as well as emissions of nitrous oxide and the shorter-lived greenhouse gas methane, should also be taken into account. Accounting for all of these factors and emissions from 1850–2021, emissions from the US are estimated to comprise approximately 17% of current global warming. {2.1}



Tami Phelps

Carbon dioxide, along with other greenhouse gases like methane and nitrous oxide, is well-mixed in the atmosphere. This means these gases warm the planet regardless of where they were emitted. For the first half of the 20th century, the vast majority of greenhouse gas emissions came from the US and Europe. But as US and European emissions have been falling (US emissions in 2021 were 17% lower than 2005 levels), emissions from the rest of the world, particularly Asia, have been rising rapidly. The choices the US and other countries make now will determine the trajectory of climate change and associated impacts for many generations to come (Figure 1.13). {2.1, 2.3; Ch. 32}



George Lorio

Box 1.4. Global Warming Levels

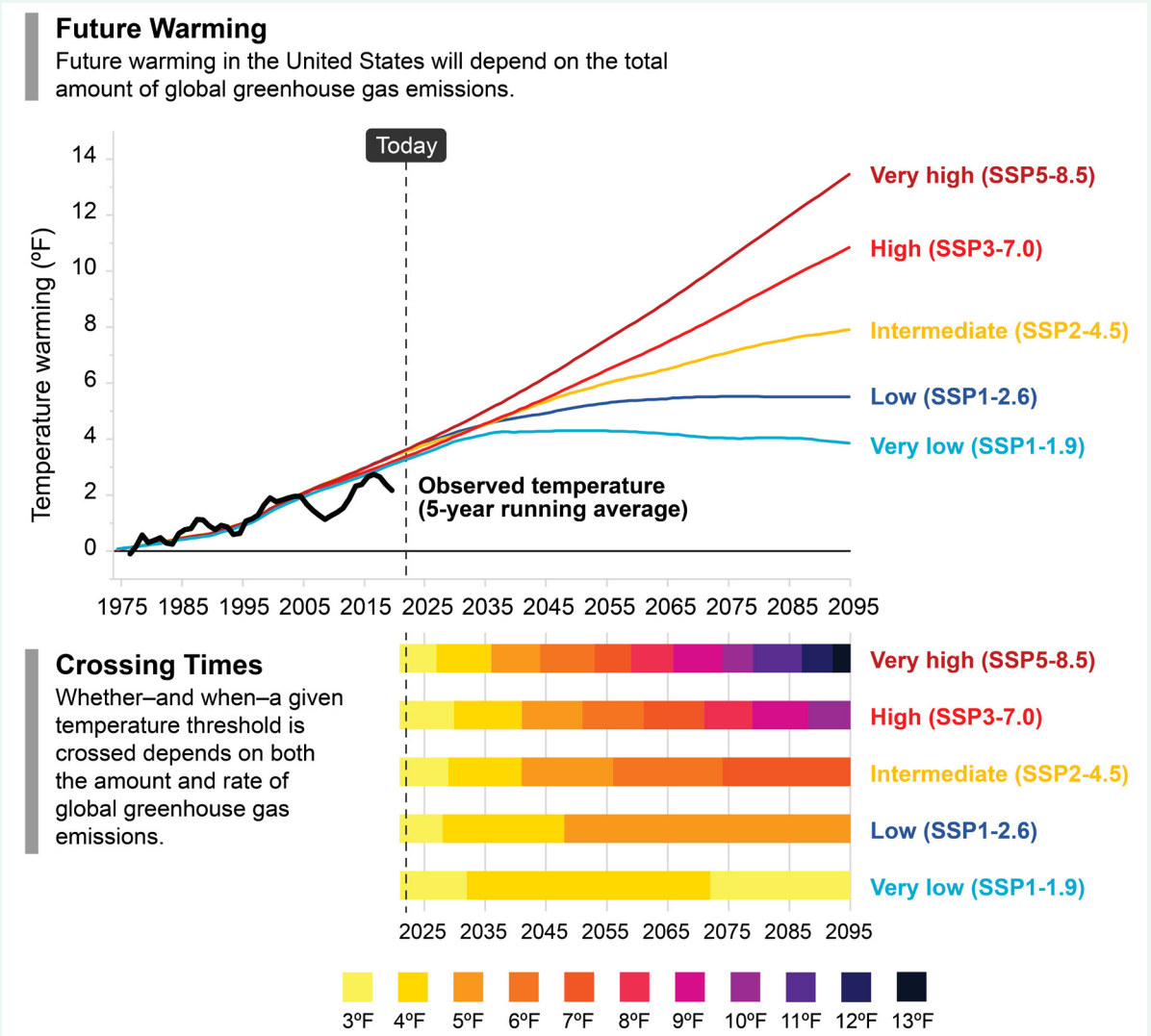
Because long-term societal actions are uncertain, climate modeling experts use different scenarios of plausible futures to represent a range of possible trajectories. These scenarios capture variables such as the relationship between human behavior, greenhouse gas emissions, Earth's responses to changes in the concentration of greenhouse gases in our atmosphere and ocean, and the resulting impacts, including temperature change and sea level rise. {3.3; Guide to the Report; App. 3}

Since there are uncertainties inherent in all of these factors—especially human behavior and the choices that determine emissions levels—the resulting range of projections are not predictions but instead reflect multiple potential future pathways. Future climate change under a given scenario is often expressed in one of two ways: as a range of potential outcomes in a future year (Figure 1.13a) or the time at which a specific outcome is expected (Figure 1.13b). {2.3, 3.3; App. 3}

Over the next decade, projected global warming is very similar across all scenarios. Updating energy infrastructure or making systemic economic and political changes takes time, thus temperature trajectories under different scenarios take time to diverge. {2.3}

By midcentury (2040–2070), differences between projected temperatures under higher and lower scenarios become apparent. By the end of the century, the global warming level—that is, how much the global average surface temperature increases above preindustrial levels—is expected to exceed 5.4°F (3°C) under high and very high scenarios (SSP3-7.0 and SSP5-8.5, respectively), and the world could see more than 7.2°F (4°C) of warming under a very high scenario (SSP5-8.5). Long-term global warming is expected to stay below 3.6°F (2°C) under a low scenario (SSP1-2.6) and can be limited to 2.7°F (1.5°C) only under a very low scenario (SSP1-1.9). {2.3}

The risk of exceeding a particular global warming level depends on future emissions. This means that projections are conditional: when or if the world reaches a particular level of warming is largely dependent on human choices. {2.3}



Potential Warming Pathways in the United States

When or if the US reaches a particular level of warming depends on global greenhouse gas emissions from human activities.

Figure 1.13. How much warming the US will experience—and when a given temperature threshold is crossed—depends on future global emissions. The **top graph** shows observed change in US surface temperature during 1975–2022 (black line, 5-year averaged) and modeled historical (1975–2014) and projected (2015–2095) change in surface temperature compared to 1951–1980, annually averaged over all 50 states and Puerto Rico under different climate scenarios (multicolored lines; see Table 3 in the Guide to the Report). The **bottom graph** shows the same projections in a different way, highlighting the year in which the US crosses temperature thresholds under each scenario. The vertical dashed line represents the year 2023. Data for the US-Affiliated Pacific Islands and the US Virgin Islands are not available. See Figure 1.5 for observed US and global temperature changes since 1895. Adapted with permission from Figure TS.1 in Arias et al. 2021.

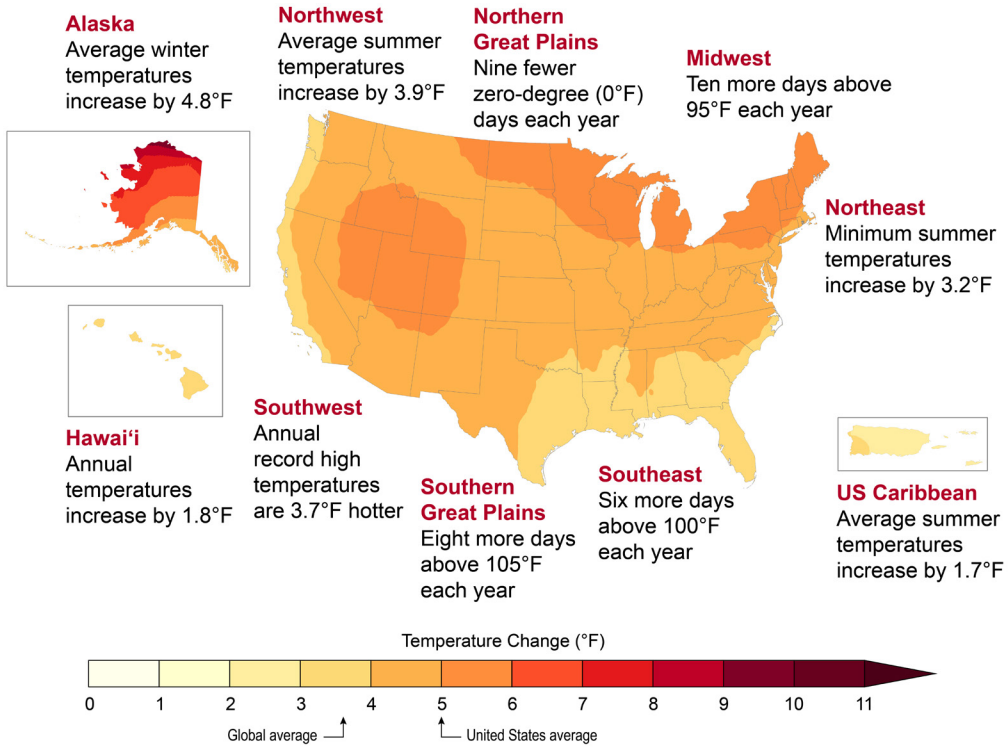
Rising global emissions are driving global warming, with faster warming in the US

The observed global warming of about 2°F (1.1°C) over the industrial era is unequivocally caused by greenhouse gas emissions from human activities, with only very small effects from natural sources. About three-quarters of total emissions and warming (1.7°F [0.95°C]) have occurred since 1970. Warming would have been even greater without the land and ocean carbon sinks, which have absorbed more than half of the CO_2 emitted by humans. {2.1, 3.1, 7.2; Ch. 2, Introduction; Figures 3.1, 3.8}

The US is warming faster than the global average, reflecting a broader global pattern: land areas are warming faster than the ocean, and higher latitudes are warming faster than lower latitudes. Additional global warming is expected to lead to even greater warming in some US regions, particularly Alaska (Figure 1.14). {2.1, 3.4; Ch. 2, Introduction; App. 4}

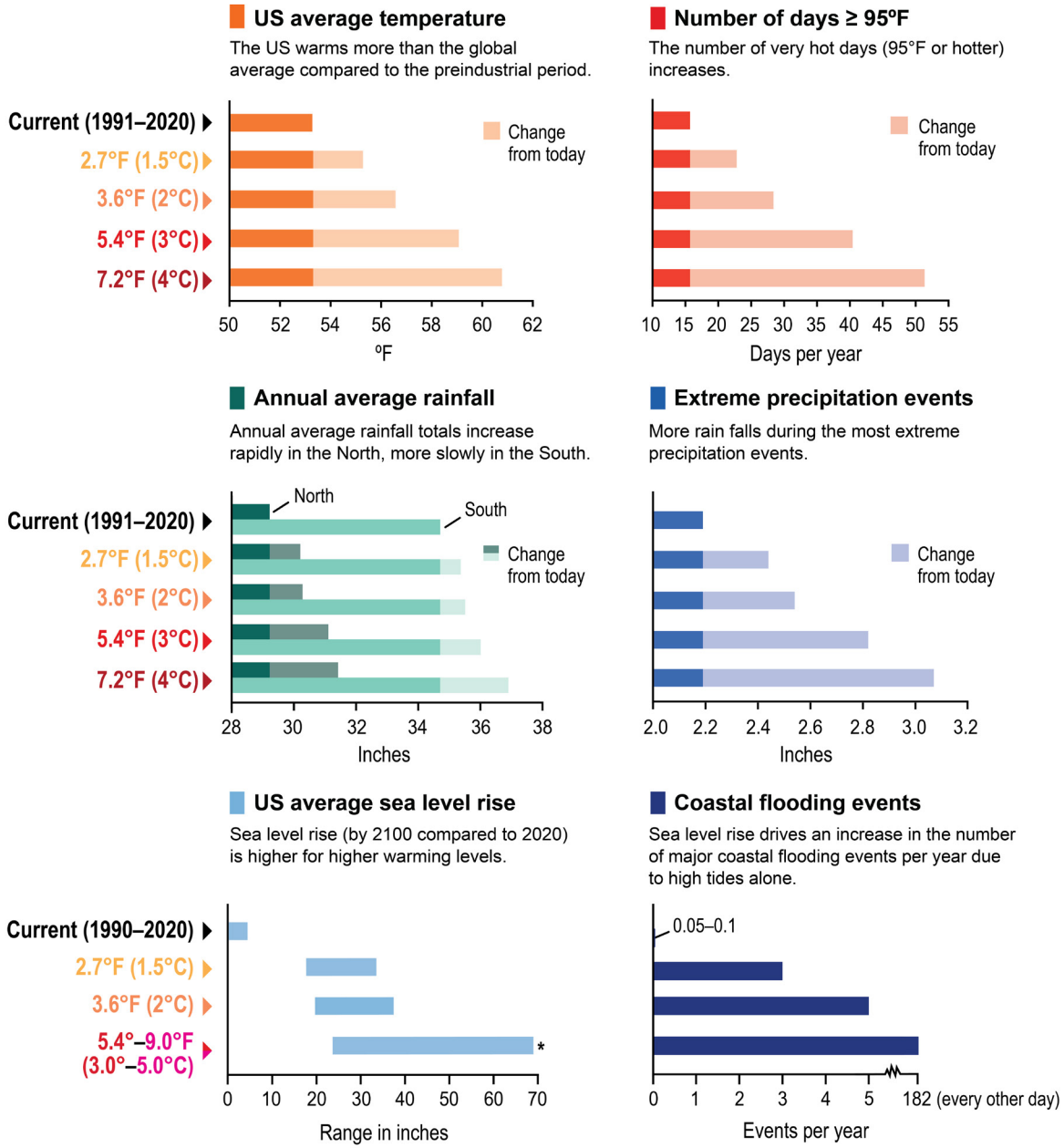
Warming increases risks to the US

Rising temperatures lead to many large-scale changes in Earth's climate system, and the consequences increase with warming (Figure 1.15). Some of these changes can be further amplified through feedback processes at higher levels of warming, increasing the risk of potentially catastrophic outcomes. For example, uncertainty in the stability of ice sheets at high warming levels means that increases in sea level along the continental US of 3–7 feet by 2100 and 5–12 feet by 2150 are distinct possibilities that cannot be ruled out. The chance of reaching the upper end of these ranges increases as more warming occurs. In addition to warming more, the Earth warms faster in high and very high scenarios (SSP3-7.0 and SSP5-8.5, respectively), making adaptation more challenging. {2.3, 3.1, 3.4, 9.1}



What would 3.6°F (2°C) of global warming feel like in the United States?

Figure 1.14. As the world warms, the United States warms more on average. The map shows projected changes in annual surface temperature compared to the present day (1991–2020) under a global warming level of 3.6°F (2°C) above preindustrial levels (see Figure 2.9). Regional examples show how different temperature impacts would be experienced across the country at this level of warming. Figure credit: USGCRP, NOAA NCEI, and CISESS NC.



*Rise at the upper end of this range cannot be ruled out due to the possibility of rapid ice sheet loss. The amount of warming required to trigger such loss is not currently known but is assessed to be above 3.6°F (2°C).

Consequences Are Greater at Higher Global Warming Levels

At higher global warming levels, the US will experience more severe climate impacts.

Figure 1.15. With each additional increment of global warming, climate impacts in the US are projected to be more severe: US average temperature warms more than the global average (**top left**), and the number of days per year at or above 95°F in the US increases (**top right**). Annual average US rainfall increases rapidly in the North and more slowly in the South (**center left**), and more rain falls during the most extreme precipitation events (**center right**). Sea level rise (range of projected increases by 2100 compared to 2020) is higher (**bottom left**), driving an increase in the number of major coastal flooding events per year due to high tides alone (**bottom right**). Temperature (averages and extremely hot days; top row) and extreme rainfall projections (center right) are averages for all 50 states and Puerto Rico. Average rainfall projections (center left) are shown for both the northern and southern US (above and below 37° latitude, respectively). Sea level rise (bottom left) and coastal flooding (bottom right) projections are averages for the contiguous United States. For sea level change estimates outside of the contiguous US, see Chapter 23 (for Puerto Rico and the US Virgin Islands), Chapter 30 (for Hawai'i and the US-Affiliated Pacific Islands), and Sweet et al. 2022 (for Alaska). Global warming levels refer to warming since preindustrial temperature conditions, defined as the 1851–1900 average. Figure credit: USGCRP, NOAA NOS, NASA, NOAA NCEI, and CISESS NC.

How Climate Action Can Create a More Resilient and Just Nation

Large near-term cuts in greenhouse gas emissions are achievable through many currently available and cost-effective mitigation options. However, reaching net-zero emissions by midcentury cannot be achieved without exploring additional mitigation options. Even if the world decarbonizes rapidly, the Nation will continue to face climate impacts and risks. Adequately and equitably addressing these risks involves longer-term inclusive planning, investments in transformative adaptation, and mitigation approaches that consider equity and justice.

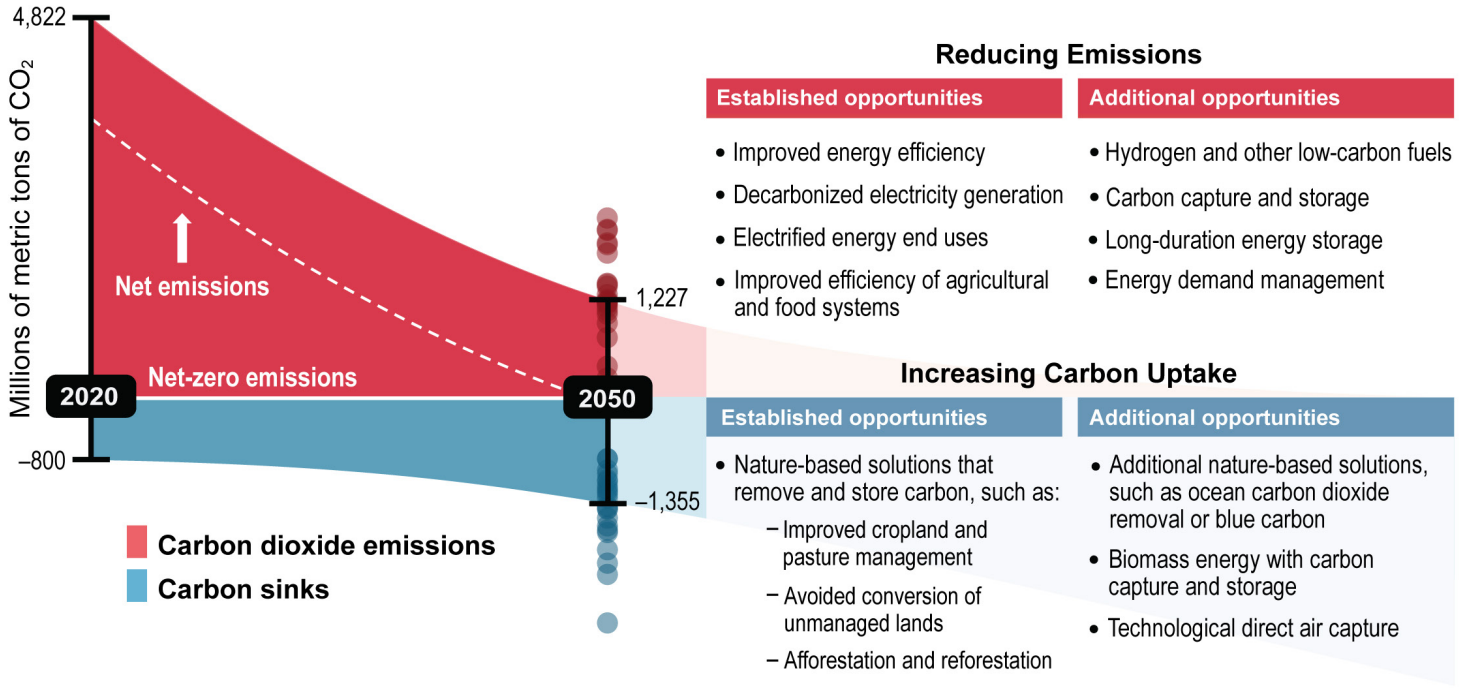
Available mitigation strategies can deliver substantial emissions reductions, but additional options are needed to reach net zero

Limiting global temperature change to well below 2°C (3.6°F) requires reaching net-zero CO_2 emissions globally by 2050 and net-zero emissions of all greenhouse gases from human activities within the following few decades (see "Meeting US mitigation targets means reaching net-zero emissions" above). Net-zero emissions pathways involve widespread implementation of currently available and cost-effective options for reducing emissions alongside rapid expansion of technologies and methods to remove carbon from the atmosphere to balance remaining emissions. However, to reach net-zero emissions, additional mitigation options need to be explored (Figure 1.16). Pathways to net zero involve large-scale technological, infrastructure, land-use, and behavioral changes and shifts in governance structures. {5.3, 6.3, 9.2, 9.3, 10.4, 13.2, 16.2, 18.4, 20.1, 24.1, 25.5, 30.5, 32.2, 32.3; Focus on Blue Carbon}

Scenarios that reach net-zero emissions include some of the following key options:

- Decarbonizing the electricity sector, primarily through expansion of wind and solar energy, supported by energy storage {32.2}
- Transitioning to transportation and heating systems that use zero-carbon electricity or low-carbon fuels, such as hydrogen {5.3, 13.1, 32.2, 32.3}
- Improving energy efficiency in buildings, appliances, and light- and heavy-duty vehicles and other transportation modes {5.3, 13.3, 32.2}
- Implementing urban planning and building design that reduces energy demands through more public transportation and active transportation and lower cooling demands for buildings {12.3, 13.1, 32.2}
- Increasing the efficiency and sustainability of food production, distribution, and consumption {11.1, 32.2}
- Improving land management to decrease greenhouse gas emissions and increase carbon removal and storage, with options ranging from afforestation, reforestation, and restoring coastal ecosystems to industrial processes that directly capture and store carbon from the air {5.3, 6.3, 8.3, 32.2, 32.3; Focus on Blue Carbon}

Portfolio of Mitigation Options for Achieving Net Zero by 2050



Reaching net zero by 2050 in the US will involve a mix of reductions in greenhouse gas emissions and increases in carbon dioxide removal.

Figure 1.16. Reaching net-zero emissions (horizontal white line) by midcentury in the US would mean deep reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases (**top side of figure**; red), with residual emissions balanced by additional removal of CO_2 from the atmosphere (**bottom side of figure**; blue). The dashed white line shows net emissions to the atmosphere (the sum of carbon sources and carbon sinks). The dots at 2050 show ranges of emissions and uptake for energy model scenarios explored in detail in Chapter 32. Model scenarios that achieve these targets project a mix of established opportunities for reducing emissions and increasing carbon sinks. Among these, energy efficiency, decarbonized electricity (mainly renewables), and end-use electrification are critical for the energy sector. While not exhaustive, the list also includes additional opportunities, many of which are emerging technologies that will be integral to reaching net zero. These include options like use of hydrogen and low-carbon fuels to further reduce emissions in difficult-to-decarbonize sectors and greatly increasing CO_2 removal. Figure credit: EPA; University of California, Irvine; NOAA NCEI; and CISESS NC.

Due to large declines in technology and deployment costs over the last decade (Figure 1.2), decarbonizing the electricity sector is expected to be largely driven by rapid growth in renewable energy. Recent legislation is also expected to increase deployment rates of low- and zero-carbon technology. To reach net-zero targets, the US will need to add new electricity-generating capacity, mostly wind and solar, faster than ever before. This infrastructure expansion may drastically increase demand for products (batteries, solar photovoltaics) and resources, such as metals and critical minerals. Near-term shortages in minerals and metals due to increased demand can be addressed by increased recycling, for example, which can also reduce dependence on imported materials. {5.2, 5.3, 17.2, 25.3, 32.2, 32.4; Focus on Risks to Supply Chains}

Most US net-zero scenarios require CO_2 removal from the atmosphere to balance residual emissions, particularly from sectors where decarbonization is difficult. In these scenarios, nuclear and hydropower capacity are maintained but not greatly expanded; natural gas–fired generation declines, but more slowly if coupled with carbon capture and storage. {32.2}

Nature-based solutions that restore degraded ecosystems and preserve or enhance carbon storage in natural systems like forests, oceans, and wetlands, as well as agricultural lands, are cost-effective mitigation strategies. For example, with conservation and restoration, marine and coastal ecosystems could capture and store enough atmospheric carbon each year to offset about 3% of global emissions (based on 2019 and 2020 emissions). Many nature-based solutions can provide additional benefits, like improved ecosystem resilience, food production, improved water quality, and recreational opportunities. {8.3; Boxes 7.2, 32.2; Focus on Blue Carbon}

Adequately addressing climate risks involves transformative adaptation

While adaptation planning and implementation has advanced in the US, most adaptation actions to date have been incremental and small in scale (see Table 1.3). In many cases, more transformative adaptation will be necessary to adequately address the risks of current and future climate change. {31.1, 31.3}.

Table 1.3. Incremental Versus Transformative Adaptation Approaches

	Examples of incremental adaptation	Examples of transformative adaptation
	Using air-conditioning during heatwaves	Redesigning cities and buildings to address heat
	Reducing water consumption during droughts	Shifting water-intensive industry to match projected rainfall patterns
	Elevating homes above flood waters	Directing new housing development to less flood-prone areas

Transformative adaptation involves fundamental shifts in systems, values, and practices, including assessing potential trade-offs, intentionally integrating equity into adaptation processes, and making systemic changes to institutions and norms. While barriers to adaptation remain, many of these can be overcome with financial, cultural, technological, legislative, or institutional changes. {31.1, 31.2, 31.3}.

Adaptation planning can more effectively reduce climate risk when it identifies not only disparities in how people are affected by climate change but also the underlying causes of climate vulnerability. Transformative adaptation would involve consideration of both the physical and social drivers of vulnerability and how they interact to shape local experiences of vulnerability and disparities in risk. Examples include understanding how differing levels of access to disaster assistance constrain recovery outcomes or how disaster damage exacerbates long-term wealth inequality. Effective adaptation, both incremental and transformative, involves developing and investing in new monitoring and evaluation methods to understand the different values of, and impacts on, diverse individuals and communities. {9.3, 19.3, 31.2, 31.3, 31.5}

Transformative adaptation would require new and better-coordinated governance mechanisms and cooperation across all levels of government, the private sector, and society. A coordinated, systems-based approach can support consideration of risks that cut across multiple sectors and scales, as well as the development of context-specific adaptations. For example, California, Florida, and other states have used informal regional collaborations to develop adaptation strategies tailored to their area. Adaptation measures that are designed and implemented using inclusive, participatory planning approaches and leverage coordinated governance and financing have the greatest potential for long-term benefits, such as improved quality of life and increased economic productivity. {10.3, 18.4, 20.2, 31.4}



Ritika S.



Joan Hart

Mitigation and adaptation actions can result in systemic, cascading benefits

Actions taken now to accelerate net emissions reductions and adapt to ongoing changes can reduce risks to current and future generations. Mitigation and adaptation actions, from international to individual scales, can also result in a range of benefits beyond limiting harmful climate impacts, including some immediate benefits (Figure 1.1). The benefits of mitigation and proactive adaptation investments are expected to outweigh the costs. {2.3, 13.3, 14.5, 15.3, 17.4, 22.1, 31.6, 32.4; Introductions in Chs. 17, 31}

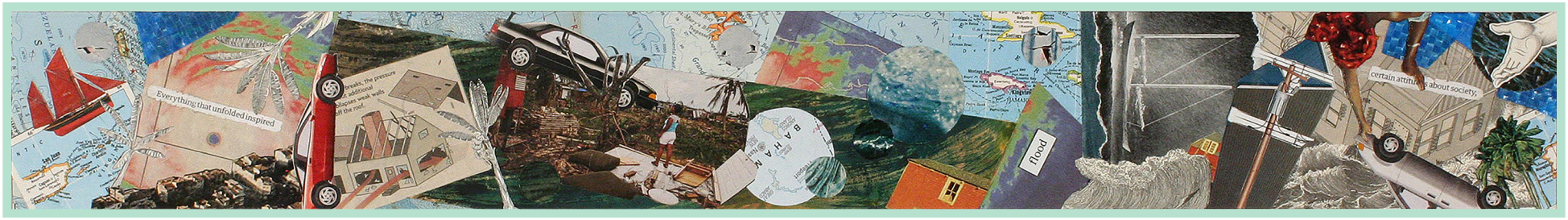
- Accelerating the deployment of low-carbon technologies, expanding renewable energy, and improving building efficiency can have significant near-term social and economic benefits like reducing energy costs and creating jobs. {32.4}
- Transitioning to a carbon-free, sustainable, and resilient transportation system can lead to improvements in air quality, fewer traffic fatalities, lower costs to travelers, improved mental and physical health, and healthier ecosystems. {13.3}
- Reducing emissions of short-lived climate pollutants like methane, black carbon, and ozone provides immediate air quality benefits that save lives and decrease the burden on healthcare systems while also slowing near-term warming. {11.1, 14.5, 15.3}
- Green infrastructure and nature-based solutions that accelerate pathways to net-zero emissions through restoration and protection of ecological resources can improve water quality, strengthen biodiversity, provide protection from climate hazards like heat extremes or flooding, preserve cultural heritage and traditions, and support more equitable access to environmental amenities. {8.3, 15.3, 20.3, 24.4, 30.4; Focus on Blue Carbon}
- Strategic planning and investment in resilience can reduce the economic impacts of climate change, including costs to households and businesses, risks to markets and supply chains, and potential negative impacts on employment and income, while also providing opportunities for economic gain. {9.2, 19.3, 26.2, 31.6; Focus on Risks to Supply Chains}
- Improving cropland management and climate-smart agricultural practices can strengthen the resilience and profitability of farms while also increasing soil carbon uptake and storage, reducing emissions of nitrous oxide and methane, and enhancing agricultural efficiency and yields. {11.1, 24.1, 32.2}

Climate actions that incorporate inclusive and sustained engagement with overburdened and underserved communities in the design, planning, and implementation of evidence-based strategies can also reduce existing disparities and address social injustices. {24.3, 31.2, 32.4}

Transformative climate actions can strengthen resilience and advance equity

Fossil fuel–based energy systems have resulted in disproportionate public health burdens on communities of color and/or low-income communities. These same communities are also disproportionately harmed by climate change impacts. {13.4, 15.2, 32.4}

A "just transition" is the process of responding to climate change with transformative actions that address the root causes of climate vulnerability while ensuring equitable access to jobs; affordable, low-carbon energy; environmental benefits such as reduced air pollution; and quality of life for all. This involves reducing impacts to overburdened communities, increasing resources to underserved communities, and integrating diverse worldviews, cultures, experiences, and capacities into mitigation and adaptation actions. As the country shifts to low-carbon energy industries, a just transition would include job creation



Melanie Mills

and training for displaced fossil fuel workers and addressing existing racial and gender disparities in energy workforces. For example, Colorado agencies are creating plans to guide the state's transition away from coal, with a focus on economic diversification, job creation, and workforce training for former coal workers. The state's plan also acknowledges a commitment to communities disproportionately impacted by coal power pollution. {5.3, 13.4, 14.3, 15.2, 16.2, 20.3, 31.2, 32.4; Figure 20.1}

A just transition would take into account key aspects of environmental justice:

- Recognizing that certain people have borne disparate burdens related to current and historical social injustices and, thus, may have different needs
- Ensuring that people interested in and affected by outcomes of decision-making processes are included in those procedures through fair and meaningful engagement
- Distributing resources and opportunities over time, including access to data and information, so that no single group or set of individuals receives disproportionate benefits or burdens

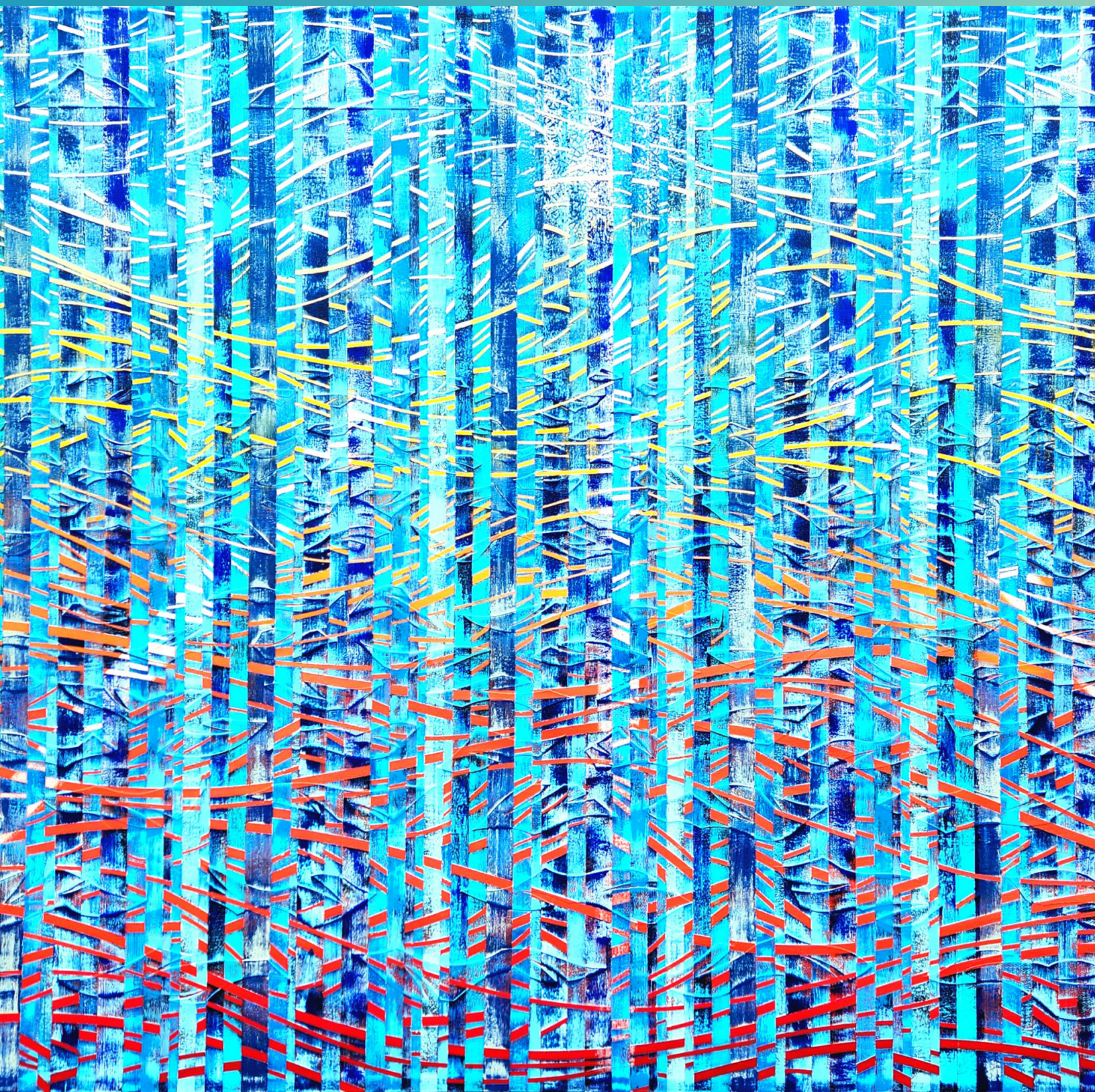
{20.3; Figure 20.1}

An equitable and sustainable US response to climate change has the potential to reduce climate impacts while improving well-being, strengthening resilience, benefiting the economy, and, in part, redressing legacies of racism and injustice. Transformative adaptation and the transition to a net-zero energy system come with challenges and trade-offs that would need to be considered to avoid exacerbating or creating new social injustices. For example, transforming car-centric transportation systems to emphasize public transit and walkability could increase accessibility for underserved communities and people with limited mobility—if user input and equity are intentionally considered. {13.4, 20.3, 31.3, 32.4; Ch. 31, Introduction}

Equitable responses that assess trade-offs strengthen community resilience and self-determination, often fostering innovative solutions. Engaging communities in identifying challenges and bringing together diverse voices to participate in decision-making allows for more inclusive, effective, and transparent planning processes that account for the structural factors contributing to inequitable climate vulnerability. {9.3, 12.4, 13.4, 20.2, 31.4}

Fifth National Climate Assessment: Chapter 2

Climate Trends



Chapter 2. Climate Trends

Authors and Contributors

Federal Coordinating Lead Author

Wenying Su, NASA Langley Research Center

Chapter Lead Author

Kate Marvel, Project Drawdown

Agency Chapter Lead Author

Roberto Delgado, National Science Foundation

Authors

Sarah Aarons, University of California San Diego, Scripps Institution of Oceanography
Abhishek Chatterjee, NASA Jet Propulsion Laboratory, California Institute of Technology
Margaret E. Garcia, Arizona State University
Zeke Hausfather, Stripe Inc.
Katharine Hayhoe, Texas Tech University
Deanna A. Hence, University of Illinois at Urbana–Champaign
Elizabeth B. Jewett, National Oceanic and Atmospheric Administration
Alexander Robel, Georgia Institute of Technology
Deepti Singh, Washington State University Vancouver
Aradhna Tripati, University of California, Los Angeles
Russell S. Vose, NOAA National Centers for Environmental Information

Review Editor

Caroline P. Normile, Bipartisan Policy Center

Cover Art

Dodd Holsapple

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Introduction

Human activities are changing the climate. The evidence for warming across multiple aspects of the Earth system is incontrovertible, and the science is unequivocal that increases in atmospheric greenhouse gases are driving many observed trends and changes (KM 3.1). There are more greenhouse gases in the atmosphere primarily because humans have burned and continue to burn fossil fuels for transportation and energy generation.[1] Industrial processes, deforestation, and agricultural practices also increase greenhouse gases in the atmosphere.[1] As a result of increases in the atmospheric concentrations of these heat-trapping gases, the planet is on average about 2°F (1.1°C) warmer than it was in the late 1800s.[2,3,4,5] No natural processes known to science could have caused this long-term temperature trend. The only credible explanation for the observed warming is human activities (Ch. 3).

Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970. This temperature change has driven increases in the frequency and severity of some extreme events, consistent with the scientific understanding of climate change (Ch. 3). There has always been extreme weather, which occurs even in an unchanged climate due to the natural variability of the Earth system. However, recent advances in attribution science (KM 3.3) mean that the role of climate change in some extreme events can now be quantified in real time.[6,7] For example, climate change made the record-breaking Pacific Northwest heatwave of June 2021 2° to 4°F hotter,[8] and in 2017, Hurricane Harvey's rainfall was estimated to be about 15%–20% heavier than it would have been without human-caused warming.[9,10,11]

Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018,[12] although some estimates put heat-related mortality closer to 1,300 deaths annually.[13,14] Disasters are now coming more frequently and causing more damage. In the 1980s, the country experienced, on average, one (inflation-adjusted) billion-dollar weather disaster every four months.[15] Now there is one, on average, every three weeks.[15]

Disaster risk in a complex society such as the United States is never determined simply by extreme weather events. It also depends strongly on exposure (who or what lies in the path of hazards) and vulnerability (their ability to cope with hazards). Climate change interacts with existing social, political, and economic structures—increases in property values as well as increased development in hazard hotspots[16] have also contributed to the increase in billion-dollar disasters—and exacerbates existing inequalities. Certain groups are more vulnerable to extreme events due to socioeconomic or demographic factors. Americans over 65 are several times more likely to die of heat-related cardiovascular disease than younger people, while Black Americans die from heat-related diseases at a rate twice that of the general population.[17] The extreme rainfall brought by Hurricane Harvey increased the flooded area in the Greater Houston area by 14%,[18] which led to 32% more homes flooded in Harris County,[19] with a disproportionate impact on low-income Hispanic neighborhoods. The spatial distribution of climate impacts partially reflects current and past policy choices: low-income neighborhoods, including those historically affected by redlining or other discriminatory policies, can be as much as 12°F hotter during heatwaves than wealthier neighborhoods in the same city[20] and are at a substantially higher risk of flooding.[21]

Climate change has other wide-ranging consequences for people's health and well-being (KM 15.1) and the land and ocean ecosystems on which we depend (Chs. 8, 10). The 2021 Pacific Northwest heatwave, which resulted in more than 1,400 heat-related fatalities, also led to widespread die-offs of shellfish and other marine organisms (Box 10.1), tree and crop damage, and other impacts on the region's ecosystems.[15,22] Western wildfires, made more severe by climate change (Focus on Western Wildfires), have destroyed towns and infrastructure and contributed to an increase in the frequency and persistence of high levels of

air pollution across the US West (Chs.14, 15).[23] These extreme events occur against a changing backdrop as climate change pushes aspects of the Earth system into a "new normal."

Long-term warming trends are associated with shifts in other aspects of the climate system. For example, both drought in the western US[24] and heavier precipitation and increased flood risk across much of the US[25] are linked to rising temperatures (KM 3.5). Sea level rise threatens the coasts (Ch. 9; Figure A4.10) and makes storm surges higher. Scientists cannot rule out the possibility of still more dramatic shifts if certain tipping elements trigger rapid and irreversible changes. While immediate and aggressive reductions in greenhouse gas emissions can mitigate future warming (KM 32.2) and reduce the risk of exceeding tipping points, temperatures will continue to increase until emissions of carbon dioxide reach net zero. When or if warming stops, long-term responses to the temperature changes that have already occurred will continue to drive changes for decades. Put simply, communities across the country are built for a climate that no longer exists.

Key Message 2.1

Climate Is Changing, and Scientists Understand Why

It is unequivocal that human activities have increased atmospheric levels of carbon dioxide and other greenhouse gases. It is also unequivocal that global average temperature has risen in response. Observed warming over the continental United States and Alaska is higher than the global average (*virtually certain, very high confidence*). Long-term changes have been observed in many other aspects of the climate system (*very high confidence*). The Earth system is complex and interconnected, which means changes in faraway regions are *virtually certain* to affect the United States (*very high confidence*).

Humans are increasing atmospheric concentrations of planet-warming gases, including the three main greenhouse gases produced by human activities: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O; Table 2.1; Figure A4.3). Since 1850, carbon dioxide concentrations have increased by more than 47%, nitrous oxide by 23%, and methane by more than 156%.[1] Methane is a more potent greenhouse gas than CO_2 but is shorter-lived and present in lower concentrations than CO_2. Nitrous oxide is both long-lived and more potent, but its concentrations are also lower than CO_2. Strong reductions in emissions of both CO_2 and non-CO_2 greenhouse gases are required to limit human-induced global warming to specific levels.[26]

Table 2.1. Concentrations of Greenhouse Gases That Cause Global Warming Are Increasing

Human activities have increased atmospheric concentrations of the three main greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Shown below are the concentrations in 1850 and 2020 for all three gases, along with information on the atmospheric lifetimes, sources, and sinks (processes by which the gas is removed from the atmosphere).

Greenhouse Gas	1850 Concentration	2020 Concentration	Lifetime	Sources	Sinks
Carbon dioxide (CO_2)	280 parts per million (ppm)[27]	412 ppm[28]	See below*	Human activities: fossil fuel use, industrial processes, and changes in land use such as deforestation, land clearing for agriculture, and soil degradation. Natural sources: oceans, animal and plant respiration, decomposition, forest fires, volcanic eruptions.	Uptake by the biosphere on land and ocean and formation of calcium carbonate and carbonate ion leading to ocean acidification and land-based weathering
Methane (CH_4)	700 parts per billion (ppb)[29]	1,878 ppb[30]	9.1 ± 0.09 years	Human activities: agriculture, waste management, energy use, and biomass burning. Natural sources: geological, oceanic hydrates, permafrost, termites, wild animals.	Chemical reactions in the atmosphere and soil uptake
Nitrous oxide (N_2O)	270 ppb[1]	333 ppb[31]	116 ± 9 years[32]	Human activities: agriculture, fossil fuel combustion, biomass/ biofuel burning, and wastewater; atmospheric nitrogen deposition on ocean and land. Natural sources: rivers, estuaries and coastal zones, open oceans, soils under natural vegetation, atmospheric chemistry.	Stratospheric destruction via photolysis or broken down by chemical reactions

* Carbon dioxide's lifetime cannot be represented with a single value since CO_2 moves among different reservoirs within the ocean–atmosphere–land system (see "Carbon Cycle," App. 5). The rate at which this transfer of CO_2 happens between reservoirs can vary from months to thousands of years, thus making it unrealistic to provide a single numerical value for the lifetime of CO_2, unlike CH_4 and N_2O, which have specific chemical loss mechanisms in the atmosphere. Also see https://www.epa.gov/climate-indicators/greenhouse-gases.

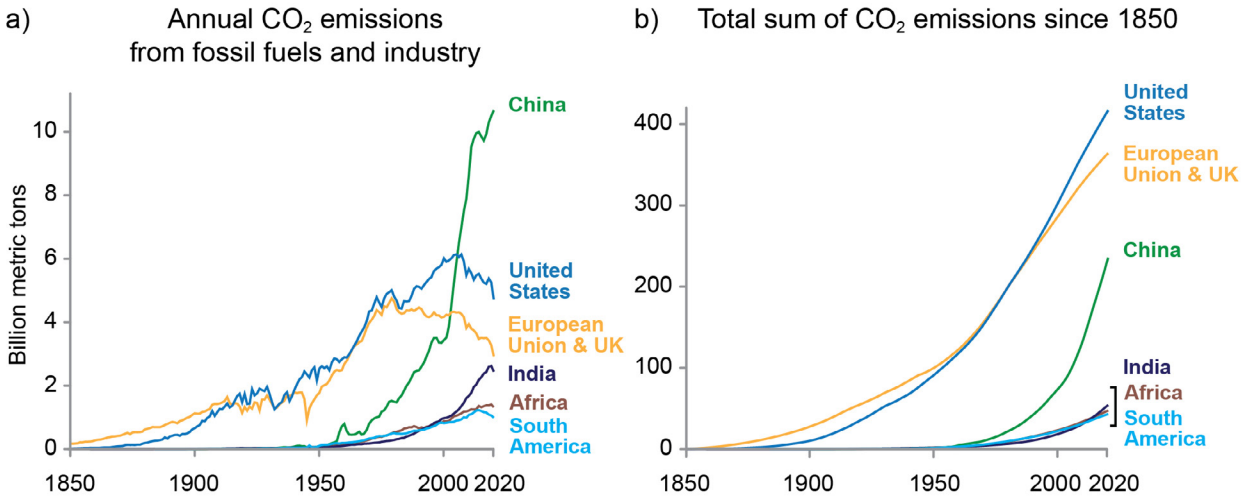
CO_2 Emitted Long Ago Continues to Contribute to Climate Change Today

The carbon dioxide not removed from the atmosphere by natural sinks lingers for thousands of years. This means CO_2 emitted long ago continues to contribute to climate change today. The long lifetime of atmospheric CO_2 is one of the primary reasons why the COVID-19 pandemic–related reduction in greenhouse gas emissions—a decrease of 7% between 2019 and 2020[33,34,35]—had no measurable impact on atmospheric CO_2 concentrations and little effect on global temperatures (Focus on COVID-19 and Climate Change).[36,37] Because of historical trends, cumulative CO_2 emissions from fossil fuels and industry in the US are higher than from any other country (Figure 2.1b).

Carbon dioxide, along with other greenhouse gases like methane and nitrous oxide, is well-mixed in the atmosphere. This means these gases warm the planet regardless of where they were emitted, and all countries that emit them contribute to the warming of the entire globe. For the first half of the 20th century, the vast majority of greenhouse gas emissions came from the United States and Europe, but emissions from the rest of the world, particularly Asia, have been rising rapidly (Figure 2.1a). In 2021, for example, US emissions were 17% lower than 2005 levels and falling. Currently, the country that emits the most CO_2 on an annual basis is China.

In order to understand the total contributions of past actions to observed climate change, additional warming from CO_2 emissions from land use, land-use change, and forestry, as well as emissions of nitrous oxide and the shorter-lived greenhouse gas methane, should also be taken into account alongside cumulative fossil CO_2 emissions. Accounting for all these factors and emissions from 1850–2021, US emissions are estimated to comprise approximately 17% of current global warming, China 12%, European Union 10%, and emissions from the 47 least-developed countries collectively 6%.[38] The present is shaped by the past; future global warming depends on decisions made today (KM 2.3).

Greenhouse Gas Emissions from the US and Other Sources



China is now the largest single-country emitter of carbon dioxide on an annual basis. The United States and Europe have emitted the majority of cumulative carbon dioxide.

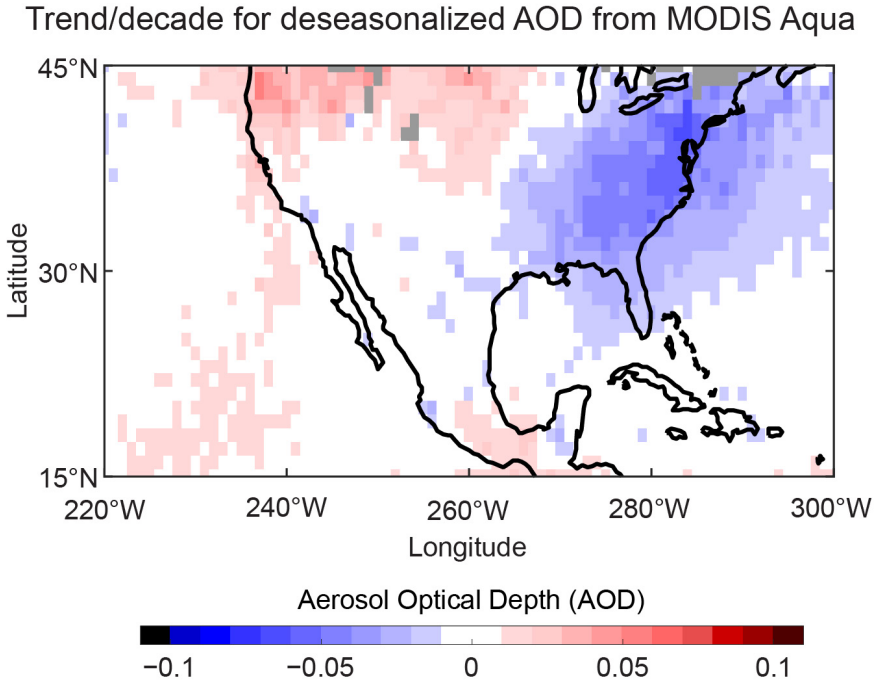
Figure 2.1. Panel (**a**) shows the annual total carbon dioxide (CO_2) emissions from fossil fuels and industry for selected world regions. China is currently the world's largest emitter of CO_2. Emissions from the US and the European Union and UK are large and falling; India, Africa, and South America emit less CO_2 on an annual basis. Panel (**b**) shows the cumulative CO_2 emissions of the same world regions. Some CO_2 emitted decades ago remains in the atmosphere today, causing the climate changes now being experienced. Figure credit: Project Drawdown.

Greenhouse Gases Are Not the Only Air Pollutants That Affect the Climate

Many of the human activities that produce greenhouse gases also produce small airborne particles known as aerosols. Aerosol emissions are an important constituent of air pollution, which is responsible for more excess deaths in the United States than murders and car accidents combined.[39] Aerosols also have climate impacts: they can scatter or absorb sunlight, which have cooling and warming effects, respectively.

Aerosols also affect climate through their effects on clouds (Ch. 3). Increased global aerosol emissions have primarily cooled the planet, partially counteracting the warming caused by greenhouse gases, but compared to CO_2 aerosols are more localized and shorter lived. Aerosol emissions in the US have dramatically decreased since the passage of the Clean Air Act and subsequent pollution control legislation (Figure 2.2), global aerosol emissions have fallen, and the location of peak aerosol emissions has shifted from North America and Europe to South and East Asia. COVID-19–related shutdowns (see Focus on COVID-19 and Climate Change) led to decreases in aerosol emissions, reducing their cooling effect. This led to a small and temporary global warming estimated at 0.05°F.[40] Long-term reductions in aerosol emissions would further reduce the cooling effect of aerosols,[41,42] which means that even stronger reductions in greenhouse gases would be required to limit warming to specific levels.

Observed Trends in Aerosol Optical Depth from 2002 to 2021



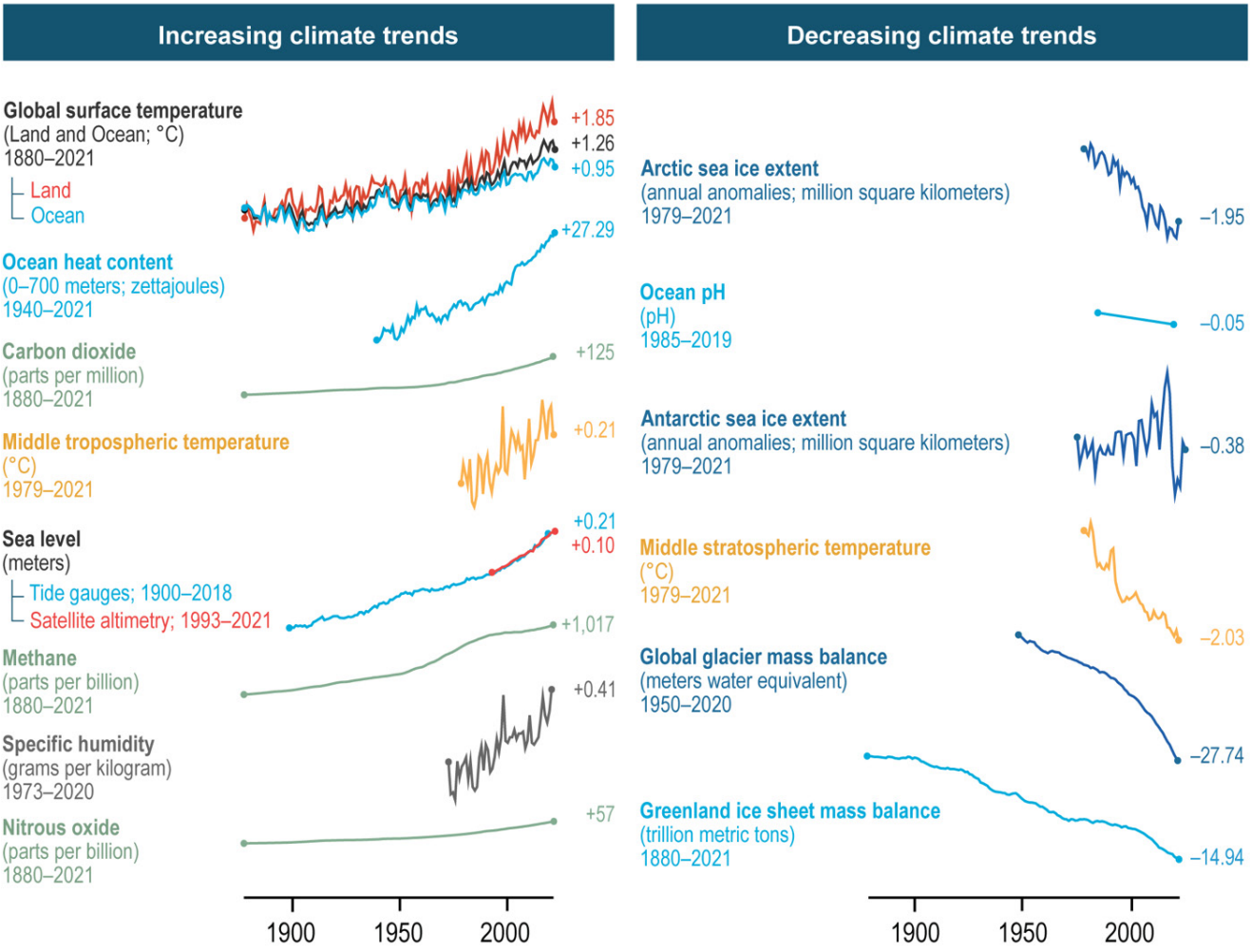
Trends in aerosol optical depth show decreases in aerosol pollution across the eastern United States.

Figure 2.2. Aerosol pollution over and downwind of the eastern US has decreased significantly in recent decades, resulting in both improved air quality and reduced cooling effects. Aerosols are tiny particles in the air that are associated with respiratory disease. Reduction of these particles means less impact on human health. These particles also reflect sunlight back to space, thus cooling the Earth's atmosphere. Reduction of these particles means less sunlight is reflected resulting in reduced cooling effects. This figure shows the trend from July 2002 to December 2021 in aerosol optical depth (AOD), a unitless measure of the total amount of aerosols in the atmosphere, as derived from satellite observations. The trend is calculated from deseasonalized AOD anomaly and is shown as change per decade. The trend over and downwind of the eastern US is significant at the 95% confidence level. Figure credit: NASA Langley Research Center.

Climate Change Is Already Here

Global average temperatures over the past decade (2012–2021) were close to 2°F (1.1°C) warmer than the preindustrial period (1850–1899).[2,3,4,5] This warming has been accompanied by several large-scale changes: loss of glaciers, ice sheet mass, and sea ice; ocean warming, acidification, and deoxygenation; increases in ocean heat content and marine heatwaves; increases in atmospheric humidity; shifting rainfall patterns and more frequent heavy precipitation; seasonal shifts including shorter winters and earlier spring and summer seasons; and changes in the biosphere (such as land and ocean species shifting poleward). Global average sea levels over the past decade were also higher than in the preindustrial period by between 7 and 9.5 inches, with more than half of this rise occurring since 1980.[43,44,45] A subset of notable global climate trends is shown in Figure 2.3.

Evidence for Climate Change Across Multiple Variables



Changes across the Earth system reflect the influence of human activities on the climate.

Figure 2.3. Climate change is apparent in many different aspects of the Earth system between 1880 and 2021. Many of these changes are evidence for a human fingerprint on the climate, reflecting the current scientific understanding of how the planet responds to external influences (Ch. 3). Global changes between the start and end of each time series are shown as numerical values to the right of each chart and are calculated by fitting each time series with a localized linear regression with a bandwidth of 30 years. Figure credit: Stripe Inc., NOAA NCEI, and CISESS NC.

The Changes We Face Are Unprecedented in Human History

Bubbles of ancient air trapped in ice cores can be used to reconstruct atmospheric concentrations of greenhouse gases over the last 800,000 years. These concentrations rise and fall due to natural processes, but human activities have increased greenhouse gases in the atmosphere rapidly and to levels unprecedented in the history of human life on Earth. Other paleoclimatic evidence indicates that the last time atmospheric CO_2 concentrations were as high as today was approximately 3.2 million years ago,[46,47] a time when global average sea levels were 18–63 feet higher than today.[48] Evidence from multiple proxy-based reconstructions of the past indicates that the rate of increase of global surface temperatures observed over the past several decades is unprecedented over the past 2,000 years.[49]

The Climate in the United States Is Changing

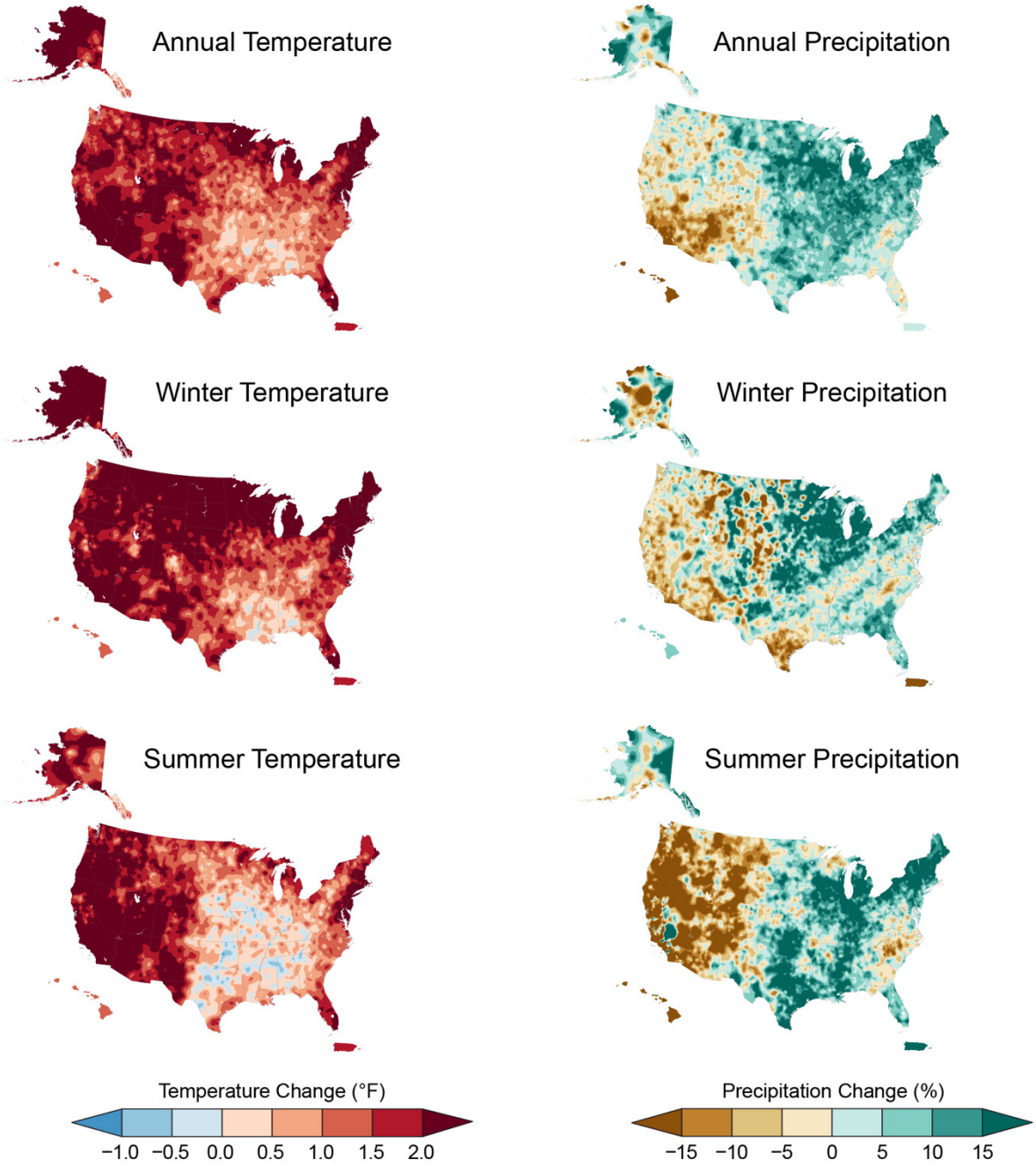
The US Is Warming Faster Than the Global Average

Temperatures in the contiguous United States (CONUS) have risen by 2.5°F and temperatures in Alaska by 4.2°F since 1970, compared to a global temperature rise of around 1.7°F over the same period. This reflects a broader global pattern in which land is warming faster than the ocean, higher latitudes are warming faster than lower latitudes, and the Arctic is warming fastest of all.[50] There are substantial seasonal and regional variations in temperature trends across the US and its territories. Winter is warming nearly twice as fast as summer in many northern states (Figure 2.4). Annual average temperatures in some areas (including parts of the Southwest, upper Midwest, Alaska, and Northeast) are more than 2°F warmer than they were in the first half of the 20th century, while parts of the Southeast have warmed less than 1°F. These regional differences are most pronounced in the summer: seasonal temperatures in some regions east of the Rockies have decreased. Studies have linked these regional trends to a combination of natural climate variability,[51,52,53,54,55] human-caused drivers such as irrigation and agricultural intensification,[56,57] and aerosol pollution (Figure 2.4; Ch. 3).[53,58] This decreasing trend has recently reversed in the southeastern US, possibly in response to decreasing aerosol amounts (Figure 2.2),[59] a shift projected to increase climate change impacts in that region (Ch. 22).

The Characteristics of Precipitation Are Changing

Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002–2021 was 5%–15% higher relative to the 1901–1960 average in the central and eastern US, a trend attributable to climate change.[60] Hawai'i (Ch. 30) and parts of the Southwest (Ch. 28) are getting drier (Figure 2.4), recording average annual precipitation decreases between 10% and 15% over the same time period. The timing of precipitation is also changing. While the Northeast and Midwest have seen wetter conditions in all seasons, the Southeast has received more precipitation in the fall but drier conditions in spring and summer.[61] Across most of the Southwest, precipitation was more than 15% below average during summer, fall, and spring and 10%–15% above average in the winter.[62,63] The Pacific Northwest also experienced drier summers and wetter winters. More precipitation is now falling as rain rather than snow, which is contributing to reductions in snowpack and maximum annual snow equivalent (Ch. 4; Figure A4.7).

Observed Changes in Annual, Winter, and Summer Temperature and Precipitation



Temperature has increased and precipitation has changed over much of the United States.

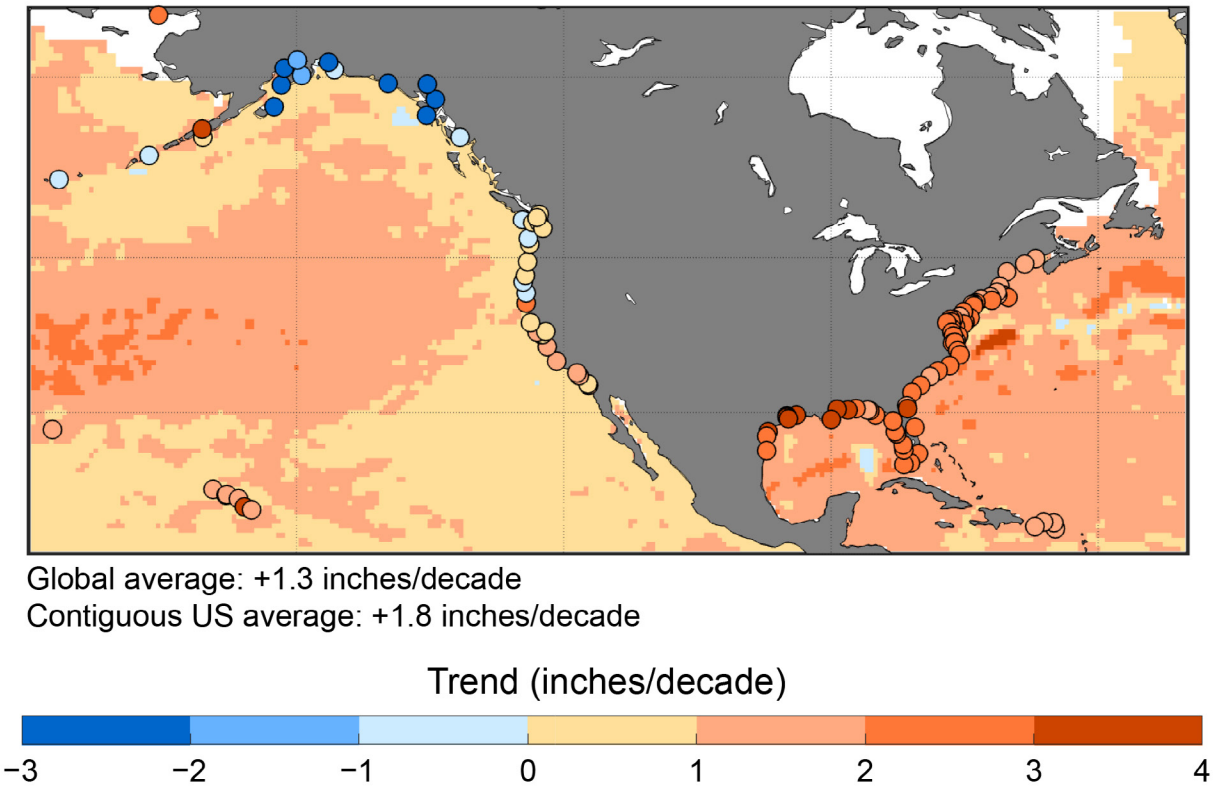
Figure 2.4. Changes shown are the difference between the annual average or seasonal temperatures (**left column**) and precipitation totals (**right column**) for the present day (2002–2021) compared to the average for the first half of the last century (1901–1960) for the contiguous United States (CONUS), Hawai'i, and Puerto Rico; and 1925–1960 for Alaska. Temperature and precipitation estimates for CONUS and Alaska are derived from the nClimGrid dataset.[64,65] For Hawai'i and Puerto Rico, temperature estimates are derived from NOAAGlobalTemp,[5] and precipitation estimates are derived from the Global Precipitation Climatology Center dataset.[66] Figure credit: NOAA NCEI and CISESS NC.

Sea Level Along the Continental US Coast Is Rising Faster Than the Global Average

Over the past century, average sea level along the continental US coastline has risen by about 11 inches, which is considerably more than the global average sea level rise of 7 inches.[67] In just the last three decades (1993–2020), sea level has risen at a rate of 1.8 inches per decade in the continental US compared to 1.3 inches per decade globally (Figure 2.5). Over the same period, the rate of sea level rise has accelerated both globally and in the continental US.[68] Within the US, rates of relative sea level rise (i.e., changes in sea level relative to local land surface heights, including local changes in land elevation) vary spatially, with the highest rates between 1993 and 2020 observed along the Gulf and Mid-Atlantic Coasts (greater than 2.4 inches per decade of sea level rise, as shown in Figure 2.5), the lowest rates in the Pacific Northwest (0–1 inches per decade of sea level rise, as shown in Figure 2.5), and relative sea level fall in Southeast Alaska.

Many processes have contributed to these regional differences. Land subsidence has driven very high rates of relative sea level rise along the Gulf Coast. Variations in ocean circulation and land subsidence have driven higher rates of sea level rise along the Mid-Atlantic Coast over recent decades.[69,70] On the Pacific Coast, ocean-circulation variation related to the Pacific Decadal Oscillation and local land uplift have caused lower rates of sea level rise and, in some places (such as Southeast Alaska), even sea level fall.[71] Changes in average sea level have doubled the frequency of disruptive high tide flooding in the continental United States over the past few decades.[72] In some cities, the increase in flood frequency has been even greater due to locally higher rates of sea level rise—for example, a fourfold increase in the frequency of disruptive high tide flooding events in Miami Beach, Florida, over the last 20 years.[73]

Observed Sea Level Trends



Sea levels are rising across most US coastal areas.

Figure 2.5. Satellite and tide gauge data show trends in sea level rise during 1993–2020 that are, on average, greater than global trends. Sea levels are not rising uniformly across US coastlines. The highest rates of sea level rise have occurred along the Gulf Coast and Atlantic Coast, with lower rates on the Pacific Coast and sea level fall along parts of the Alaska Coast. Rates of sea level rise in Hawai'i and Puerto Rico are closer to the global average. Adapted from Sweet et al. 2022.[67]

Oceans Are Changing

The oceans are warming along all US coasts, but not all areas are warming at the same rate.[74,75] Surface waters along the Alaska and Northeast coastlines are warming faster than in most other regions due to climate change impacts on weather and ocean circulation in those regions (KMs 21.2, 29.5).[76] Oxygen minimum zones (areas of the deeper ocean where oxygen levels are low) have expanded in volume since 1970, particularly in Alaska waters, with negative consequences for fisheries (Ch. 10).[77,78,79] Dead zones—areas in the coastal ocean where oxygen levels seasonally drop, sometimes causing massive die-offs of marine life—are happening in more places around the country, with climate change one of many factors contributing to their expansion.[77,80] Acidification, caused by rising levels of atmospheric CO_2 being absorbed by the ocean (KM 3.4; Figure 3.9), has changed the carbonate chemistry of US offshore and coastal waters at variable rates, impacting marine life.[81] Acidification in offshore and open ocean waters tracks the global average trends,[1] but changes in US coastal waters depend on regional upwelling conditions (Ch. 27) and acidifying contributions from land and nutrient and freshwater inputs.[82,83]

Sea and Lake Ice Is Decreasing

Sea ice has dramatically retreated from Alaska coastal seas over the last several decades at rates that exceed retreat in other parts of the Arctic Ocean (Ch. 29).[79,84] In 2018, sea ice in the Bering Sea of Alaska reached a record low at less than half the average winter extent since 1979.[85] Throughout North America and the Arctic, lake ice area and seasonal duration have also notably decreased during the satellite era (Ch. 24).[86,87]

Changes Outside National Borders Affect the United States

Warming in the Tropics Affects the Entire United States

Observed changes in atmospheric circulation are shifting the distribution of precipitation throughout the tropics and subtropics, resulting in greater precipitation variability for Caribbean and Pacific islands (Chs. 3, 23, 30).[88] These shifts are also thought to extend tropical cyclone tracks farther into the midlatitudes,[89] especially in the West Pacific basin. Tropical cyclone activity in the West Pacific has also been linked to an intensifying effect on the El Niño–Southern Oscillation (ENSO).[90,91,92] ENSO itself has tended toward more extreme events since the 1950s[93] that strongly impact the US-Affiliated Pacific Islands (Ch. 30) but also heavily influence temperature and precipitation patterns in several continental US regions,[94,95,96] as well as the development of tropical cyclones in the Pacific and Atlantic basins.[97] The tropics are also a key source of moisture for atmospheric rivers and tropical storms that bring precipitation to much of the country. As the tropics warm, the subsequent increase in moisture is intensifying the precipitation associated with these systems across the western and eastern United States.[98,99]

Ice Sheet Changes in Greenland and Antarctica Contribute to US Sea Level Rise

The pattern of mass loss from glaciers and ice sheets outside the United States also has an important influence on the spatial pattern of sea level rise along US coasts, as ice losses in Antarctica lead to more sea level increase along the US Atlantic Coast than equivalent ice losses in Greenland, due to gravitational changes associated with the redistribution of mass on the Earth's surface.[100,101] Improved estimates of sea level changes during warm periods in Earth's prehistory are now directly being used to calibrate projections of the upper bound of future sea level rise.[102,103] The closest analog for current rates of sea level rise, and those that may occur in the next century, are past warm periods when the Greenland and Antarctic ice sheets were considerably smaller than their present state and global average sea level was 10 or more feet higher.[104]

Arctic Changes Affect Weather in the Midlatitudes

The Arctic is warming faster than much of the world, and Arctic sea ice is declining rapidly as a consequence.[49] There is emerging evidence from modeling studies and observations that these changes in the Arctic are affecting atmospheric circulation and extreme weather across the United States. In summer, the temperature contrast between the Arctic and the midlatitudes has decreased, weakening the midlatitude jet stream and making certain weather regimes more persistent.[105] This has led to more persistent hot and dry extremes over parts of North America.[105,106,107] However, the connection between Arctic warming and winter weather is still uncertain. In winter, the influence of natural climate variability and the lack of consistency between observations and modeling-based studies make it difficult to connect changes occurring in the Arctic and winter severe weather.[108,109] However, some recent studies suggest that Arctic warming results in increasing disruptions of the stratospheric polar vortex that cause cold air from the Arctic to spill down over the United States, as seen in recent severe winter weather events such as the February 2021 cold snap that affected large parts of the country (Figure 26.7).[110,111,112] Notably, this Arctic air, while still cold in absolute terms, is warmer than it used to be four decades ago.

Key Message 2.2

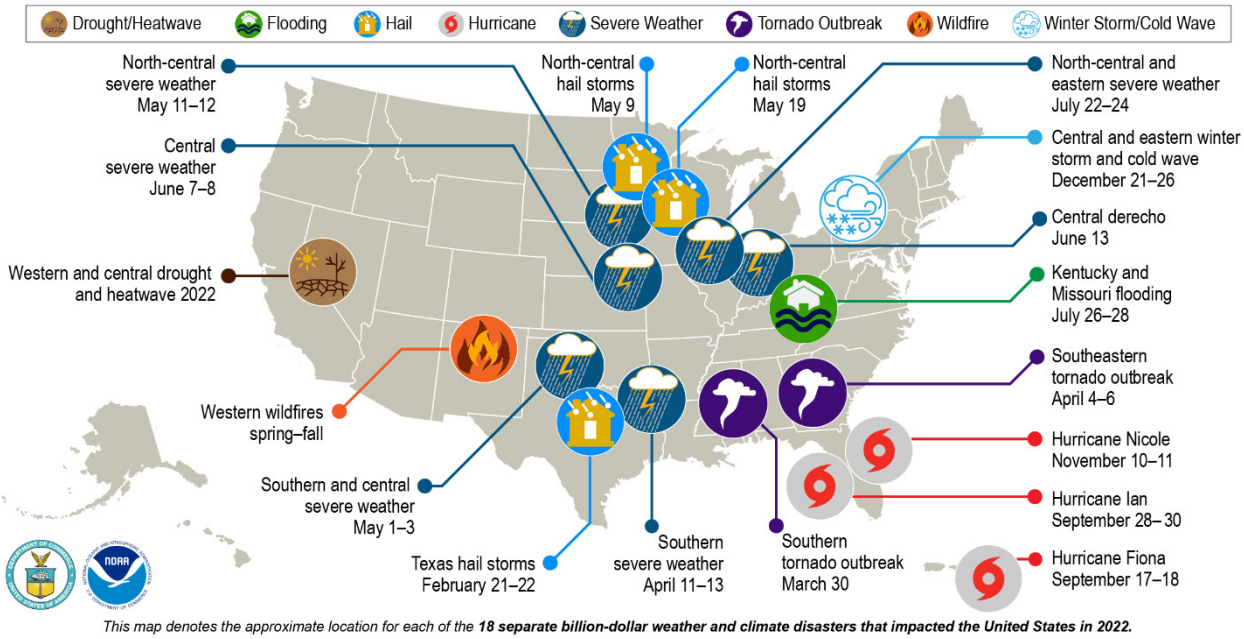
Extreme Events Are Becoming More Frequent and Severe

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*). Drought risk has been increasing in the Southwest over the past century (*very high confidence*), while at the same time rainfall has become more extreme in recent decades, especially east of the Rockies (*very high confidence*). Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*). More frequent and larger wildfires have been burning in the West in the past few decades due to a combination of climate factors, societal changes, and policies (*very high confidence*).

Climate Change Is Not Just a Problem for Future Generations, It's a Problem Today

The number and cost of weather-related disasters have increased dramatically over the past four decades, in part due to the increasing frequency and severity of extreme events and in part due to increases in exposure and vulnerability. In 2022 alone, the United States experienced 18 weather and climate disasters with damages exceeding $1 billion (Figures 2.6, A4.5). There is increasing confidence that changes in some extreme events are driven by human-caused climate change (KM 3.5).

Billion-Dollar Weather and Climate Disasters in 2022



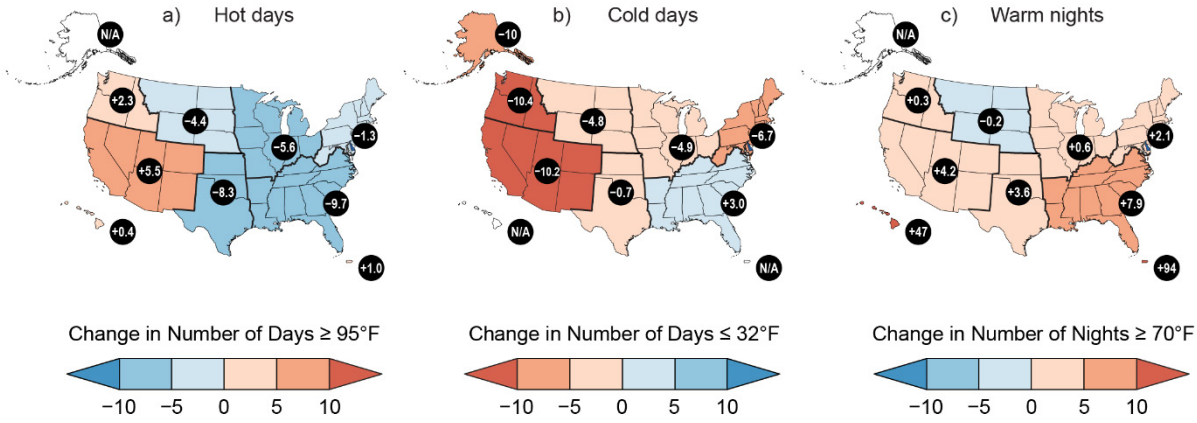
The US experienced 18 billion-dollar weather and climate disasters in 2022.

Figure 2.6. In the 1980s, there was one weather/climate disaster event with losses exceeding $1 billion approximately every four months. By the 2010s, there was one every three weeks or less. In 2022, there were 18 such events that affected the United States. These events included 1 drought event, 1 flooding event, 11 severe storm events (including tornadoes, hail storms, and straight-line winds), 3 tropical cyclone events, 1 wildfire event, and 1 winter storm event. Overall, these events resulted in the deaths of 474 people and had significant economic effects on the areas impacted. Source: NCEI 2022.[15]

The Risk of Temperature Extremes Is Changing

By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s.[113] This serves as a historical reminder of the societal consequences of extreme heat. Globally, such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021. The western US has been particularly affected by extreme heat since the 1980s (Figure 2.7), experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US.[114] By contrast, the number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades.[115,116,117] Across 50 large US cities, the US Global Change Research Program heatwave indicator (https://www.globalchange.gov/indicators/heat-waves) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.[118] Even the ocean is experiencing extreme heat: marine heatwaves—prolonged periods of discrete (from days to several months) anomalously high sea surface temperatures—have now been documented in every US marine system (KMs 8.2, 10.1, 21.2, 27.2, 28.2, 30.4; Box 10.1; Figure 29.1).[119]

Observed Changes in Hot and Cold Extremes



Hot days have increased in the West, hot nights have increased nearly everywhere, and cold days have decreased.

Figure 2.7. Over much of the country, the risk of warm nights has increased while the risk of cold days has decreased. The risk of hot days has also increased across the western US. This figure shows the observed change in the number of (**a**) hot days (days at or above 95°F), (**b**) cold days (days at or below 32°F), and (**c**) warm nights (nights at or above 70°F) over the period 2002–2021 relative to 1901–1960 (1951–1980 for Alaska and Hawai'i and 1956–1980 for Puerto Rico). Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: Project Drawdown, Washington State University Vancouver, NOAA NCEI, and CISESS NC.

The number of cold days (on which the temperature drops below freezing) has decreased across CONUS (except in the Southeast, where the number of days below freezing is small to begin with). Despite some recent damaging cold events, overall cold extremes are becoming less frequent and milder (Figure 2.7).[120,121]

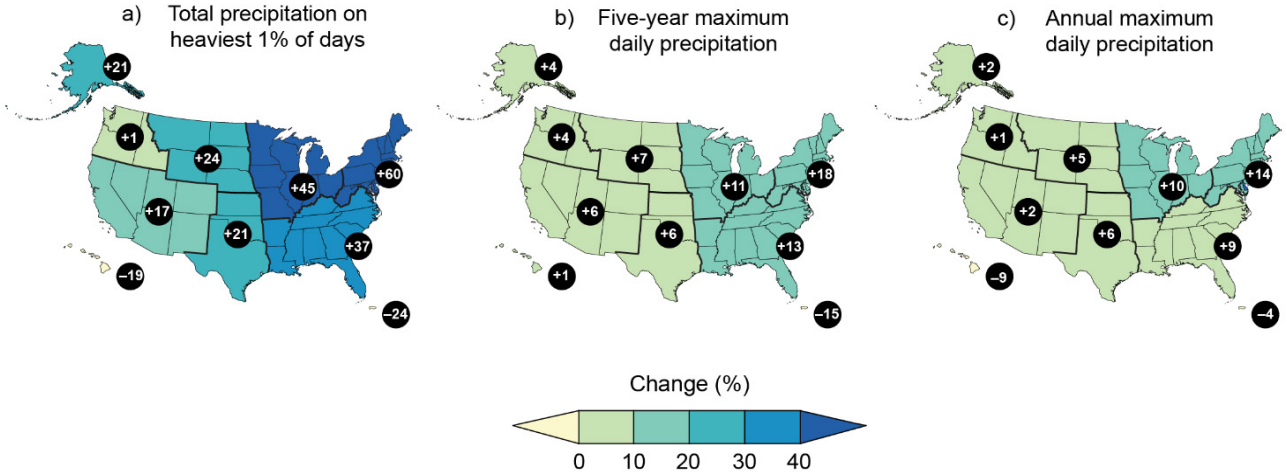
Nighttime temperatures are rising faster than daytime temperatures, and the number of nights where the temperature never falls below 70°F is increasing everywhere in the US except the Northern Great Plains (Figure 2.7). The extent of CONUS experiencing hot summer nights is growing at a faster rate than the extent experiencing hot summer days.[121,122] Temperatures are generally lower at night, allowing human (and animal) bodies, crops, and the built environment to cool down. For that reason, an increase in the frequency and intensity of warm nights can have a significant impact on human health, crop yields, and more.

Rainfall Is Becoming More Extreme

Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US (Figure 2.8).[25] This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity. The largest increase in the number of extreme precipitation days (defined as the top 1% of heaviest precipitation events) has occurred over the Northeast (an increase of around 60%) and Midwest (around 45%), along with increases of more than 10% in their annual and 5-year maximum amount (Figure 2.8). These changes have contributed to increases in river and stream flooding in these regions.[123,124] The increase in frequency and intensity of precipitation extremes is evident across a broad range of event durations (from 1 to 30 days) and return intervals (1 to 20 years), particularly east of the Rocky Mountains.[125]

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.[126,127] Paleoclimate records derived from tree-ring growth provide evidence that summer moisture has increased over the past century in parts of New England,[128] the central-eastern US,[129] and the northern Mississippi River valley.[130]

Observed Changes in the Frequency and Severity of Heavy Precipitation Events



Heavy precipitation events are becoming more frequent and intense across much of the country.

Figure 2.8. The frequency and intensity of heavy precipitation events have increased across much of the United States, particularly the eastern part of the continental US, with implications for flood risk and infrastructure planning. Maps show observed changes in three measures of extreme precipitation: (**a**) total precipitation falling on the heaviest 1% of days, (**b**) daily maximum precipitation in a 5-year period, and (**c**) the annual heaviest daily precipitation amount over 1958–2021. Numbers in black circles depict percent changes at the regional level. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credits: (a) adapted from Easterling et al. 2017;[131] (b, c) NOAA NCEI and CISESS NC.

Drought Risk Is Complex and Changing

Drought is such a complex phenomenon that it is a challenge to even define what it is: more than 150 different definitions have appeared in the scientific literature.[132] Broadly, drought results when there is a mismatch between moisture supply and demand. Meteorological drought happens when there is a severe or ongoing lack of precipitation. Hydrological drought results from deficits in surface runoff and subsurface moisture supply. Drying soil moisture affects crop yields and can lead to agricultural droughts. The timing of droughts is also complex. Droughts can last for weeks or decades. They may develop slowly over months or come on rapidly. A drought may be immediately apparent or detectable only in retrospect.

Despite this complexity, some robust regional trends are emerging. Colorado River streamflow over the period 2000–2014 was 19% lower than the 20th-century average,[133] largely due to a reduction in snowfall, less reflected sunlight, and increased evaporation.[134] The period 2000–2021 in the Southwest had the driest soil moisture of any period of the same length in at least the past 1,200 years.[135] While this drought is partially linked to natural climate variability, there is evidence that climate change exacerbated it, because warmer temperatures increase atmospheric "thirst" and dry the soil.[24,136,137,138] Droughts in the region are lasting longer[139] and reflect not a temporary extreme event but a long-term aridification trend—a drier "new normal"[140] occasionally punctuated by periods of extreme wetness consistent with expected increases in precipitation volatility in a warming world.[141,142]

The Southwest is the only region in which the total area of unusually dry soil moisture is increasing.[143] In the eastern regions of the country, hydrological droughts have become less frequent since the late 19th century due to increases in precipitation that compensate for warming-driven increases in evaporation (Figures 2.4, A4.9).[144] However, there is evidence that the likelihood of drought in the Northeast did not decrease as much as would be expected given these wetter conditions[145] and that higher increases in evapotranspiration make the Southeast more drought-prone than the Northeast (Ch. 22). Additionally, much of the US is

vulnerable to rapid-onset flash droughts that can materialize in a matter of days, driven by extreme high temperatures or wind speeds and a lack of rainfall.[146,147] These events are difficult to predict and prepare for, and can have outsized impacts.[148] There is evidence that these events are drying out soil more quickly as the world warms.[149]

Storms Are Changing

Changes in some types of storms are also apparent. Over the past three decades, heavy snowfalls have been more frequent over the Northeast,[111] a trend consistent with warming in the western Atlantic Ocean and increasingly frequent Arctic air outbreaks from polar vortex disruptions.[110] Atmospheric rivers along the Pacific Coast have become warmer over the past several decades[150] and have transported larger amounts of moisture into the West because of increases in Pacific Ocean temperatures.[151]

There is no long-term trend in the frequency of landfalling hurricanes in the United States since the late 19th century, but there has been an increase in basin-wide hurricane activity in the North Atlantic since the early 1970s.[152,153] In addition to recent increases in storm frequency, evidence continues to build that hurricanes are changing in other dangerous ways. Tropical cyclones have been intensifying more rapidly since the early 1980s,[154,155] leaving communities with less time to prepare. Hurricanes tend to lose energy as they move away from the ocean, but the rate of this hurricane decay has slowed since the 1960s, allowing storms to extend somewhat farther inland.[156] There has been a 17% decrease in the speed of movement of storms in the North Atlantic basin since 1900,[157] as well an increased tendency for storms along the North American coast to meander and stall since the 1950s.[158] Slower-moving storms can result in more heavy rainfall, wind damage, storm surge, and coastal flooding; notably, after accounting for changes in the value of property and other assets placed in harm's way, hurricane damage in the United States has generally increased since 1900.[159]

Changes in smaller-scale, short-lived severe weather such as tornadoes and thunderstorms are more difficult to assess, and direct observations of those events and the conditions associated with them are incomplete.[160] While the average annual number of tornadoes appears to have remained relatively constant, there is evidence that tornado outbreaks have become more frequent,[161] that tornado power has increased,[162] that tornado activity is increasing in the fall,[163] and that "Tornado Alley" has shifted eastward.[164] The complexes of thunderstorms that bring substantial precipitation to the central United States during the warm season have become more frequent and longer-lasting over the past two decades.[165]

Thunderstorms are associated with other important hazards, including hail and cloud-to-ground lightning. Direct observational records for these hazards are largely insufficient for identifying trends due to factors including observer biases, limited length of the record, and changes in the observing systems.[166,167] However, days with environmental conditions conducive to producing large hail (greater than 2 inches in diameter) have become more frequent over the central and eastern US and parts of the Pacific Northwest.[168]

A Combination of Factors Is Increasing Fire Risk

Much of the country is experiencing more intense and frequent wildfires associated with warming and drought[16,169] and aggravated by the reduction in Indigenous land-use and fire stewardship practices that have been critical for past management of fires.[170,171] Over the past 1,000 years, warm temperatures and droughts have tended to increase the area burned by wildfires in the West, including the Pacific Northwest and Rockies.[172] In the period 1979–2020, human-caused warming was responsible for nearly 68% of the observed increase in aridity in the West, creating the conditions that drove growth in the acreage burned by wildfires.[173] In the Rockies, higher temperatures, changes in precipitation, and fire stress have led to major ecological changes, including the disappearance of forests (Ch. 7).[174] Fire history records derived from tree rings and fire scars from forests in the Rocky Mountains show that for most of the past 2,000 years, cooler, wetter conditions, combined with Indigenous fire stewardship practices, limited fires.[171] However,

greenhouse gas–induced warming and drying and the spread of invasive vegetation types (KM 8.2) have combined with forest management policy choices and the limitation of Indigenous sovereignty to contribute to new extreme fire regimes and more frequent fires.

Lightning and human activities are both sources of wildfire ignitions in the US. Lightning is a dominant source across much of the western US and is associated with larger and more intense fires, while humans are a dominant source across the eastern US and along the Southern California coastline.[167,175,176] Both lightning-caused and human-caused fires have increased between 1992 and 2012.[175] While rising populations, development, and a growing wildland–urban interface contribute to the increase in human-caused fires,[177] there is no clear evidence of changes in lightning activity.[178,179] Changes in lightning activity are challenging to detect due to the lack of long-term satellite measurements and uncertainties in ground-based lightning detection networks.[167]

Key Message 2.3

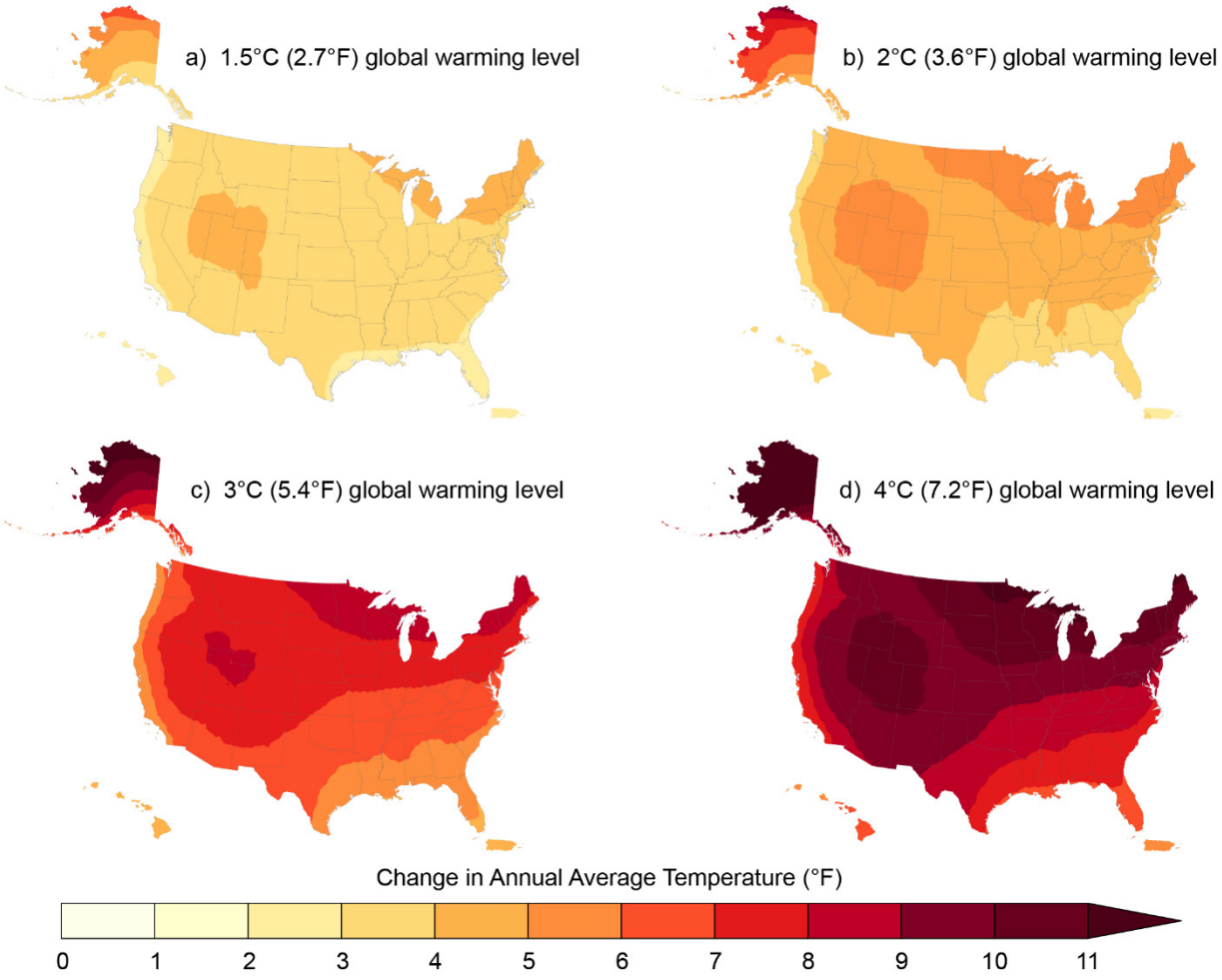
How Much the Climate Changes Depends on the Choices Made Now

The more the planet warms, the greater the impacts—and the greater the risk of unforeseen consequences (*very high confidence*). The impacts of climate change increase with warming, and warming is *virtually certain* to continue if emissions of carbon dioxide do not reach net zero (*very high confidence*). Rapidly reducing emissions would *very likely* limit future warming (*very high confidence*) and the associated increases in many risks (*high confidence*). While there are still uncertainties about how the planet will react to rapid warming and catastrophic future scenarios that cannot be ruled out, the future is largely in human hands.

As the World Warms, the United States Warms More

Every increment of global warming leads to larger increases in temperature in many regions, including much of the United States (Figure 2.9). The Paris Agreement calls for limiting global warming to "well below 2°C" relative to preindustrial temperatures, preferably to 1.5°C, and domestic and international emissions targets are generally expressed in these terms. To mirror this language, where possible, trends in this section are reported in terms of the global warming level (GWL): the global average temperature change in degrees Celsius relative to preindustrial temperatures. At a GWL of 2°C (3.6°F), the average temperature across the United States is *very likely* to increase between 4.4°F and 5.6°F (2.4°C and 3.1°C). For every additional 1°C of global warming, the average US temperature is projected to increase by around 2.5°F (1.4 °C). The northern and western parts of the country are *likely* to experience proportionally greater warming (Figure 2.9).

Projected US Temperature Changes at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



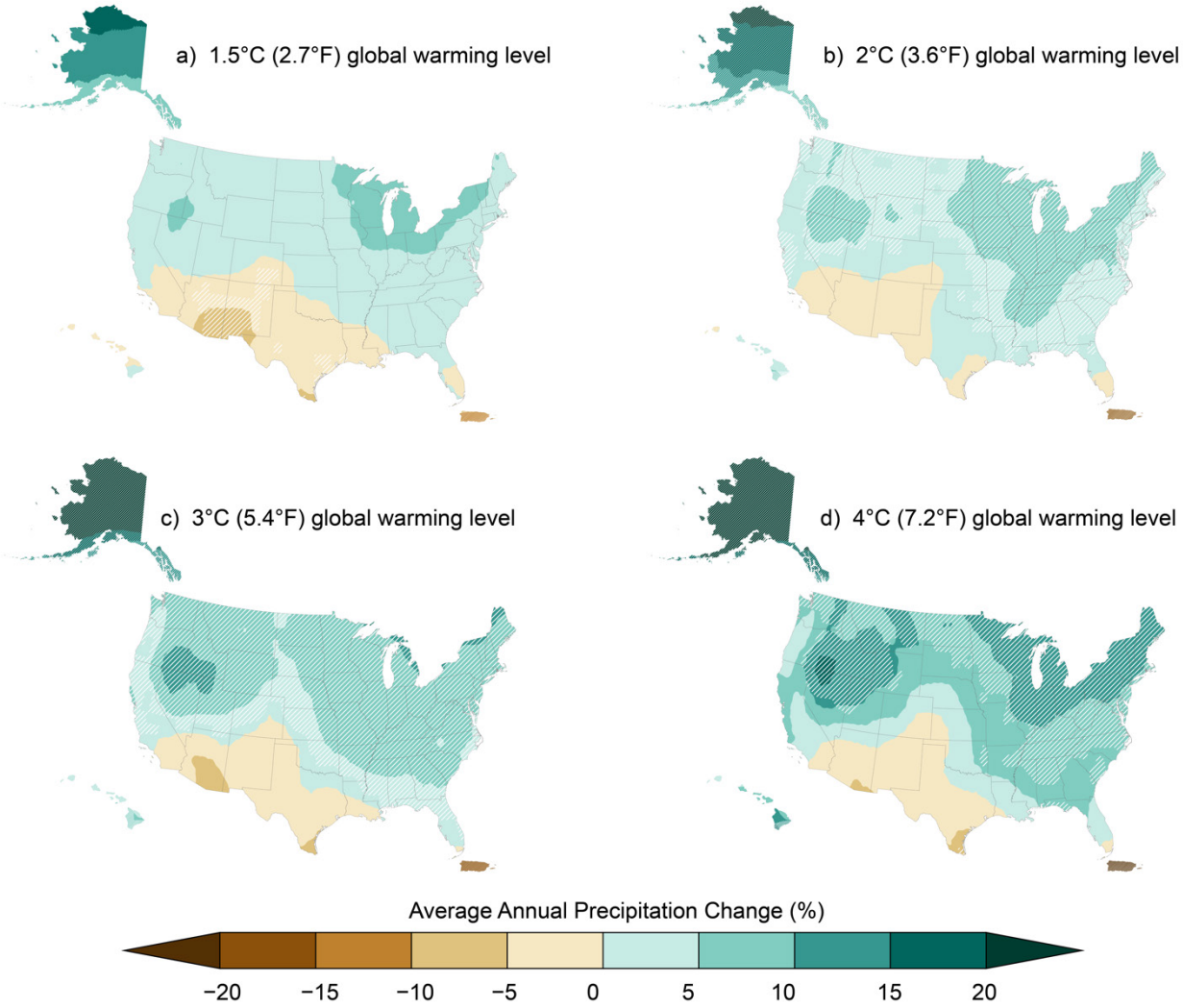
The United States is projected to warm faster than the global average.

Figure 2.9. As the world warms, the US warms more. Projected temperature rises are larger in the northern and western portions of the country and are most severe in the Arctic. These maps show projected changes in annual average temperature (°F) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1851–1900. Based on CMIP6. Data were not available for the US-Affiliated Pacific Islands. Figure credit: NOAA NCEI and CISESS NC.

Some Regions Will Get Wetter While Others Will Get Drier

Precipitation changes also scale with global warming, but these projections vary by location (Figure 2.10) and are less certain than temperature changes. As global temperatures increase, annual average precipitation is *very likely* to increase in the northern and eastern regions of CONUS and in Alaska, more likely than not to decrease in the Southwest and Texas, and *likely* to decrease in the Caribbean. Changes to the seasonal cycle of precipitation are also expected: in the Northwest, precipitation increases are *very likely* to occur during the winter wet season and decrease in the summer. In a warmer world, it is *virtually certain* that less precipitation will fall as snow, leading to large reductions in mountain snowpack and decreases in spring runoff in the mountain West (Chs. 4, 27, 28; Figure A4.7).

Projected US Precipitation Changes at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



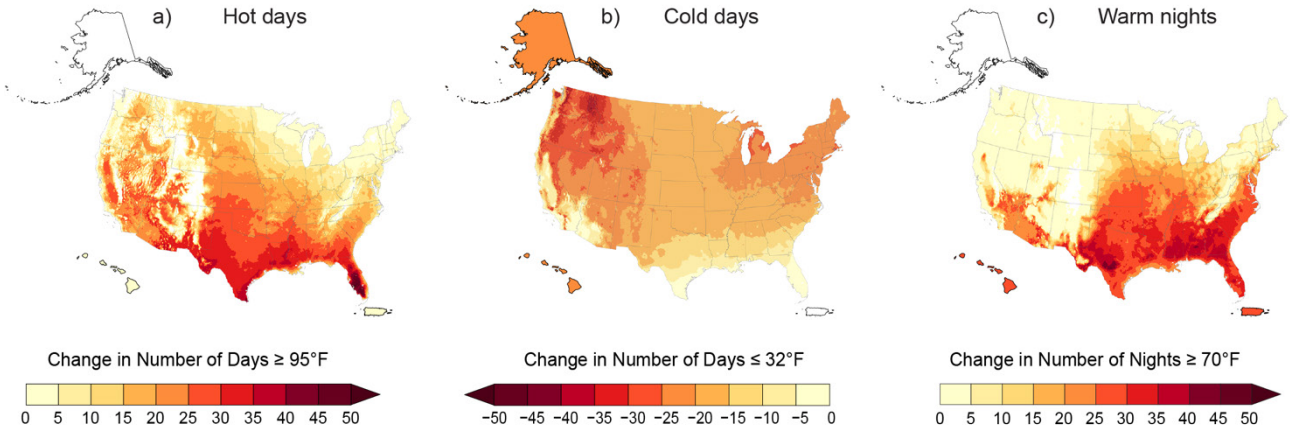
Precipitation changes are projected to be larger at higher levels of warming.

Figure 2.10. These maps show projected changes in average annual precipitation (%) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Precipitation is projected to increase with warming in the North and East and to decrease in the Southwest and the Caribbean. Changes are relative to the period 1851–1900. Based on CMIP6. Data were not available for the US Affiliated Pacific Islands. Hatching indicates areas where 80% or more of the models agree on the sign of the change. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC.

The Risk of Extreme Heat Increases with the Global Warming Level

Recent trends in extreme heat and precipitation foreshadow what is to come in a warmer world. The connection between warming and heatwaves is well understood: at the very basic level, as average temperatures warm, the risk of extreme temperatures and record-breaking temperatures goes up (Ch. 3), and it is *very likely* that heatwaves will increase in frequency, severity, and duration as warming continues. Figure 2.11a shows projected changes in the number of days at or above 95°F at a global warming level of 2°C. In addition to changes in the number of hot days, multiday heatwaves are *very likely* to last longer, affect a larger spatial extent, and become more severe, exposing more people and infrastructure simultaneously and for longer periods.[180] By contrast, the number of cold days is projected to decrease (Figure 2.11b). Nighttime temperatures are *very likely* to increase faster than daytime temperatures, leading to an increase in extreme nighttime temperatures as the global warming level increases (Figure 2.11c). Such changes in extreme heat are *very likely* to have negative impacts on human health (Ch. 15) and agricultural productivity (Ch. 11).

Projected Changes to Hot and Cold Extremes at 2°C of Global Warming



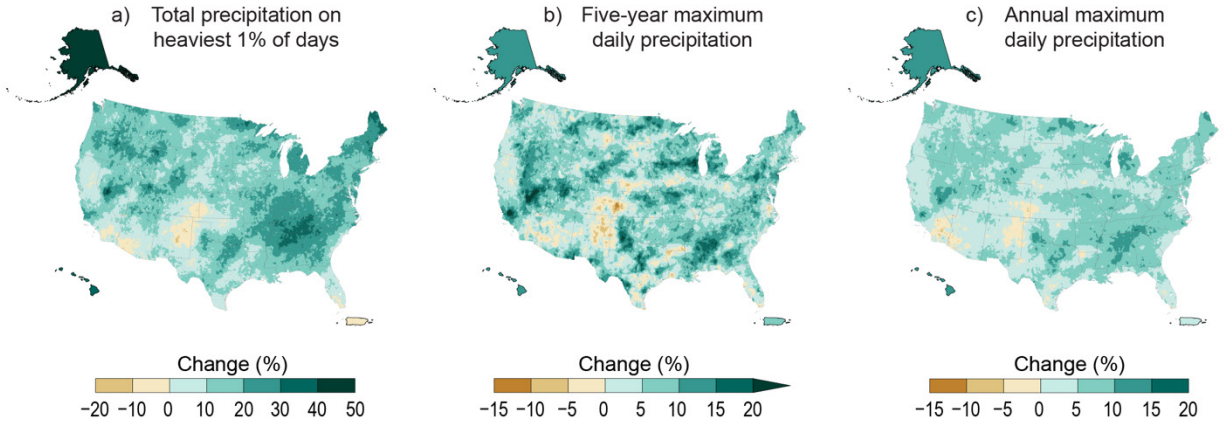
More hot days, even more warm nights, and fewer cold days are expected at a global warming level of 2°C.

Figure 2.11. These maps show changes in the (**a**) projected number of hot days with a maximum temperature at or above 95°F, (**b**) cold days (minimum temperature at or below 32°F), and (**c**) warm nights (minimum temperature at or above 70°F) at a global warming level of 2.0°C. Changes are relative to the period 1991–2020. Based on LOCA2/STAR. Values for Alaska, Hawai'i, and Puerto Rico are averages from STAR downscaling of 44, 15, and 31 stations, respectively. The Hawai'i value for cold days is for Mauna Loa, the only network station where freezing temperatures occur. Areas of no change (shown in white) generally will not experience temperatures exceeding those thresholds. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: NOAA NCEI and CISESS NC.

The Frequency and Severity of Heavy Precipitation Increases with the Global Warming Level

Extreme precipitation–producing weather systems ranging from tropical cyclones to atmospheric rivers are *very likely* to produce heavier precipitation at higher global warming levels.[127,181,182,183,184] Recent increases in the frequency, severity, and amount of extreme precipitation are expected to continue across the US even if global warming is limited to Paris Agreement targets.[126,185] Figure 2.12 shows *likely* changes at a GWL of 2°C. Changes in extreme precipitation events differ seasonally—they are *very likely* to increase in spring and winter across CONUS and Alaska and in eastern and northwestern states in the fall, while projected changes in the summer season are more uncertain.[186]

Projected Changes to Precipitation Extremes at 2°C of Global Warming



Increases in the frequency and severity of heavy precipitation are expected at a global warming level of 2°C.

Figure 2.12. The maps show projected changes in three measures of extreme precipitation at a global warming level of 2°C: (**a**) total precipitation falling on the heaviest 1% of days, (**b**) daily maximum precipitation in a 5-year period, and (**c**) the annual heaviest daily precipitation amount. Changes are relative to the period 1991–2020. Based on LOCA2/STAR. Values for Alaska, Hawai'i, and Puerto Rico are averages from STAR downscaling of 45, 16, and 31 stations, respectively. Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: NOAA NCEI and CISESS NC.

Warming-Driven Changes to the Water Balance Affect Drought Risk

Even as downpours increase, the risk of drought is also projected to rise with the global temperature. The past may provide insight into what could happen as temperatures rise. Paleoclimate datasets show that the already-water-stressed Great Basin region, which includes Nevada, parts of Utah and Wyoming, and much of the Southwest, experienced severe drought throughout the mid-Holocene (approximately 5,000–9,000 years ago), when the western Pacific was warm, Arctic temperatures were high, and there was less sea ice—all global changes that are projected in a future warmer world.[187] In the Southwest, multidecadal soil moisture droughts analogous to or drier than the 2000–2021 drought are projected to increase in the future, regardless of global warming level (Ch. 28).[188] This is due to projected decreases in springtime precipitation and earlier snowmelt that, combined with warmer temperatures, push the region into a new and drier average state.[140] However, the risk of single-year droughts analogous to the driest recent year (2002) depends strongly on the global warming level, increasing by 8% at a GWL of 2°C but by 24% at 4°C.[188] Limiting global warming would also reduce the severity of inevitable multidecadal droughts by reducing the magnitude of extreme single-year droughts during these events.

Other regions of the country are not projected to aridify to the same extent as the Southwest. However, projected changes in the amount, type, and timing of precipitation and evapotranspiration will affect the balance of water supply and demand, shaping drought risk in a warmer world. Springtime runoff from snowmelt is projected to decrease with warming in the northern and western regions of CONUS.[189] In the southern and eastern regions of the country, projected increases in winter and spring precipitation will increase moisture availability at the time soils are wettest, leading to higher runoff and flooding risk.[138] Drying of surface soils is projected to occur nearly everywhere; drying increases with the GWL due to increases in evaporative demand with warming. Deeper soil moisture projections are more uncertain,[190] but it is *likely* that total column soil moisture in the Southwest and parts of the Southern Great Plains will become drier with warming.[138]

As the Planet Warms, Storms Become More Dangerous

There is increasing evidence that a warming planet will alter the characteristics and impacts of several storm types. With every increment of global warming, projected sea level rise is *very likely* to lead to higher storm inundation levels when storms do occur (Ch. 9). Projected increases in atmospheric water vapor are *very likely* to lead to more extreme rainfall rates (Ch. 3). Projected increases in water temperatures are *very likely* to result in stronger tropical cyclones globally, with winds 5% faster (3% for the Atlantic basin) at a GWL of 2°C. It is *likely* that the overall global frequency of tropical cyclones will decrease, while the frequency of Category 4–5 hurricanes is *likely* to increase.[183] Recent research points to continued uncertainty in the future frequency of Atlantic hurricanes (e.g., Sena et al. 2022;[191] Knutson et al. 2022[192]), landfall behavior, (e.g., Zhang et al. 2020;[193] Jing et al. 2021;[194] Knutson et al. 2022[192]) and associated hazards (e.g., Gori et al. 2022[195]), as well as possible shifts to increased tropical cyclone activity in the Central Pacific (Ch. 30).[192]

Even in regions that experience an overall decrease in precipitation, atmospheric rivers are projected to become stronger and wider,[184,196] increasing the risk of downpours and floods across the western United States.[181,184,197,198] In addition, the paleoclimate record shows that the locations along the Pacific Coast where storms bring moisture may also shift with warming.[199]

It is *likely* that the frequency of weather environments that give rise to severe thunderstorms in the United States during spring and fall will increase under stronger warming scenarios.[200,201] These changes are *likely* to lengthen the severe thunderstorm season as the world warms, especially in the Midwest and Southeast during cool-season months.[202]

Warming Increases the Risk of Compound Extreme Events

The increasing risk of many individual extreme weather and climate events with warming also increases the risk that multiple extreme events may occur in quick succession in the same region. Warming also increases the risk of multiple extremes occurring simultaneously across multiple regions that are interconnected or interdependent (Focus on Compound Events). Co-occurring hot and dry conditions are projected to become more frequent with warming.[156,203,204] These conditions increase the risk of extreme wildfires, as well as affecting agriculture, water resources, and freshwater and marine ecosystems.

Co-occurring hot and moist conditions are also projected to increase with warming, and the risk of single and multiday humid-heat heatwaves across the densely populated Northeast, Southeast, and parts of the Southwest are projected to increase.[205] Higher temperatures combined with rising humidity due to the increased atmospheric moisture content are contributing to increases in humid-heat extremes—conditions that limit the ability of the human body to naturally cool down that are associated with reduced labor productivity and compounding heat-related health impacts.[206,207]

The combination of increasing drought risk and extreme precipitation are *likely* to increase the risk of extreme wildfire seasons that are followed shortly thereafter by heavy precipitation across the West,[208] which could increase the risk of postfire hazards such as debris flows, landslides, and flash floods similar to those that have affected parts of the region in recent decades (Ch. 4; Figure 3.13). The largest increases are expected in the Pacific Northwest, where this risk has historically been low.[208] Increases in hydroclimate volatility may also affect the Caribbean, Hawai'i, and some Pacific Islands (Chs. 23, 30). As global temperatures increase, the Atlantic and Gulf Coasts are projected to experience increases in compound flooding from rising sea levels that cause higher storm surge from stronger storms and heavier precipitation that result in runoff and flooding, impacting people, ecosystems, and infrastructure along the coastlines (Ch. 9).[195,209] The scientific understanding of such events continues to evolve (Focus on Compound Events).

Warming Causes Long-Term Sea Level Rise

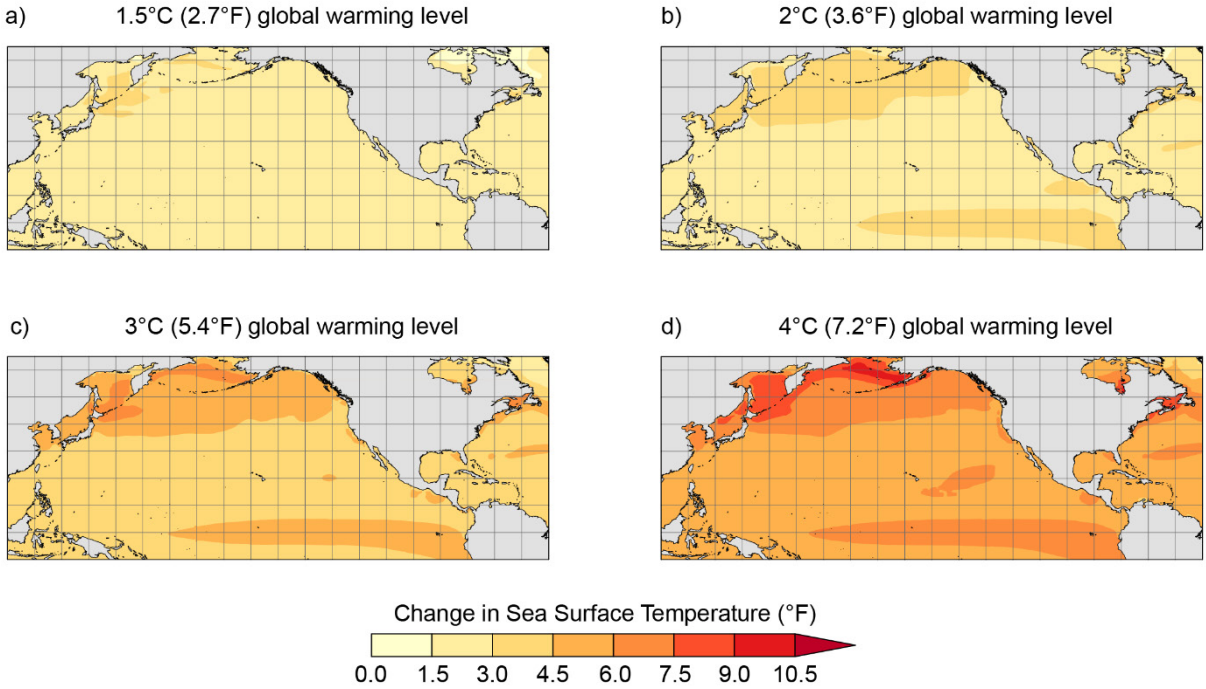
The most substantial differences in projected sea level rise for the United States for different global warming levels begin to arise at the end of this century, due to uncertainty in how much and how quickly ice will be lost from the Antarctic ice sheet.[210,211] A GWL of 2°C would lead to a *likely* sea level rise in CONUS of 2–3 feet in 2100 and 2.5–5 feet in 2150, relative to 2000 sea levels. Every additional degree Celsius of global warming is *likely* to cause at least 4 inches of additional sea level rise in CONUS in 2100 and at least 7 inches of additional sea level rise in 2150 (see Ch. 9 and Figure 9.2 for sea level projections in terms of global warming levels).[67] At a 2°C GWL, sea level rise in CONUS is not expected to exceed 4 feet in 2100 and 7 feet in 2150, although it is not considered impossible. At higher GWLs, such extreme sea level rise becomes more likely within the next 100–150 years.

The total rise in sea level that will be realized beyond 2150 can differ by many feet depending on global warming levels over the next 50–100 years due to the potential for rapid and irreversible loss of ice from Greenland and Antarctica starting next century.[102,212,213] Such significant changes at 2100 and beyond translate directly into substantially increased frequency of flooding events in coastal regions, making major flooding events in some regions as common in 2100 as minor flooding events are currently.[67] However, there are also many processes that drive local variations in sea level rise that are not clearly related to global warming levels, such as vertical land motion. To aid in planning for uncertain future sea level rise, projections are also commonly used to construct sea level scenarios,[67] which are discussed in more detail in Chapter 9 and Appendix 3.

Global Warming Changes the Oceans

Sea surface temperatures increase with the global warming level, but changes are not uniform across the globe: northern oceans are expected to warm faster than the tropics (Figure 2.13). Heat will continue to accumulate in the shallow and deep oceans: at a GWL of 4°C, ocean waters off the West Coast and Alaska could accumulate 3 billion joules per square meter, the Atlantic Coast 5 billion joules per square meter, and the Gulf of Mexico up to 6 billion joules per square meter—roughly the energy equivalent of two hundred pounds of TNT per square foot. As a result, the risk of marine heatwaves is projected to increase as the world warms. Projections indicate an increase of between 150 and 300 marine heatwave days per year if the GWL reaches 2.5°C. It is therefore possible that the coastal oceans of the United States could enter into near-permanent heatwave status, with significant ramifications for marine life.[214] The probability that September sea ice completely disappears from the Arctic Ocean, including Alaska coastal waters, rises from 1% in 2100 under a GWL of 1.5°C to 10%–30% at a GWL of 2°C.[79]

Projected Changes to Sea Surface Temperatures at 1.5°C, 2°C, 3°C, and 4°C of Global Warming



At higher global warming levels, sea surface temperatures are projected to change around the US coasts and open ocean, with implications for marine resources in those waters.

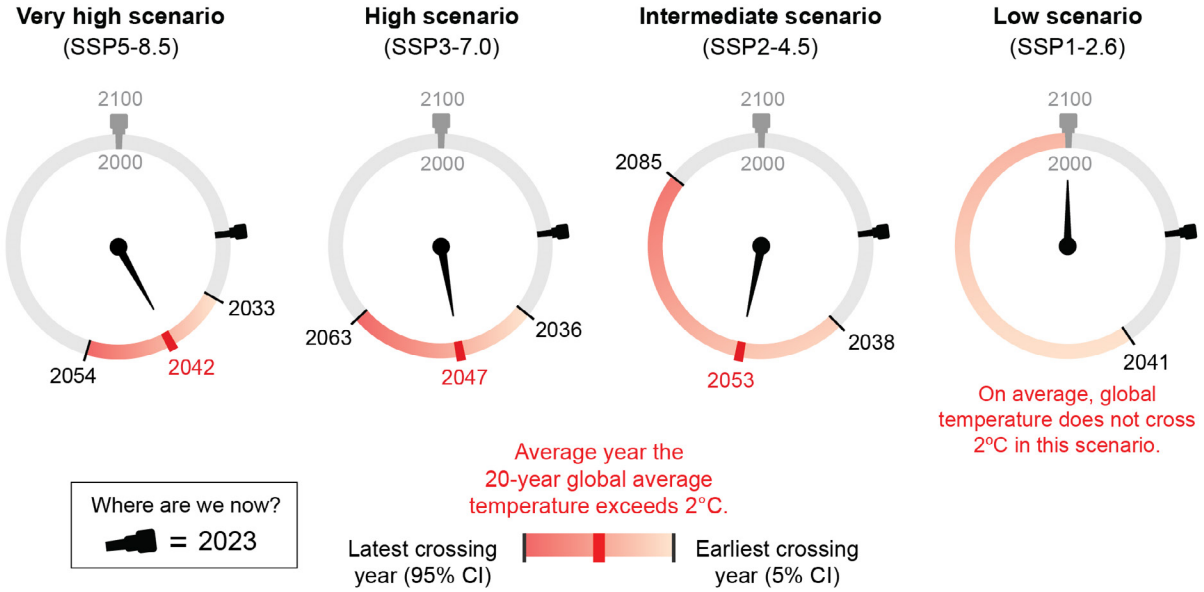
Figure 2.13. These maps show projected changes in sea surface temperatures (°F) for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1851–1900. Figure credit: NOAA, NOAA NCEI, and CISESS NC.

Projected changes in ocean acidification and oxygen loss in US waters vary with location. For higher levels of future CO_2 emissions, the chemistry of waters in the Gulf of Maine will change in ways damaging to shell-building organisms, with the saturation level of aragonite—a form of calcium carbonate used by shell-building marine life—projected to fall below a crucial shell-building threshold for most of the year.[215] Ocean oxygen loss in the upper and middle depths will be most pronounced for the United States in the North Pacific, including off the coasts of Alaska and the Pacific Coast, which will squeeze the habitats of marine life moving away from warming waters at the surface.[216,217]

When or If We Reach a Particular Global Warming Threshold Depends on Future Emissions

Projections of future global average surface temperature primarily depend on two things: 1) future emissions (Ch. 32) and 2) how sensitive the climate system is to these emissions (KM 3.2). In a very high scenario, the world is *very likely* to exceed a global warming level of 2°C between 2033 and 2054, depending on the climate sensitivity to greenhouse gas emissions (Ch. 3). In a low scenario, by contrast, the world is *very likely* not to cross this threshold at all (Figure 2.14). In addition to warming more, in high and very high scenarios, the Earth warms faster. The occurrence of some record-shattering extremes is dependent on this rate of warming.[218] Faster climate change also increases the challenge of adaptation for both human and natural systems.

Projected Global Surface Temperature Change



Future emissions of greenhouse gases determine whether and how quickly we reach 2°C of global warming.

Figure 2.14. When (or if) the world reaches 2°C of global warming depends on future greenhouse gas emissions and the sensitivity of the climate system to those emissions. Shown are the IPCC AR6 assessed warming projections for four future scenarios, with projected years at which the 2°C (3.6°F) global warming level would be reached. For example, under a very high scenario (SSP5-8.5), models project reaching 2°C between 2033 and 2054, with an average estimate of 2042. Under a low scenario (SSP1-2.6), the 5% CI (confidence interval) range begins at 2041, but the average projection shows that warming would actually stay below 2°C. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC.

Over the past few years, a number of analyses have narrowed the plausible range of current emissions outcomes based on policies in place today (see existing US mitigation policies by state, Figure 32.20), putting the world on track for a central warming estimate of around 2.6°C (ranging from 2°–3.7°C) by 2100.[219,220,221,222,223,224] Existing climate pledges, if implemented, would increase the likelihood of limiting temperature change to well below 2°C.[225] To achieve more ambitious targets, stronger action would be needed. Emissions from existing and currently planned fossil fuel infrastructure globally would put the planet on a trajectory to exceed 1.5°C in the coming decades.[226] However, current policy projections represent neither a ceiling nor a floor on future climate outcomes. Our choices matter: global surface temperatures will continue to rise until CO_2 emissions reach net zero, and surface temperatures are not expected to fall for centuries in the absence of net-negative emissions. At the same time, Earth system models suggest that only a small amount of additional surface temperature change is expected over the next few centuries if CO_2 emissions reach net zero and there are deep reductions in other greenhouse gases, at least under scenarios where global warming is limited to 2°C or below by 2100.[227] In other words, additional warming over the next few centuries is not necessarily "locked in" after net CO_2 emissions fall to zero.

Some Impacts Are Inevitable Because of Past Choices

While most models project that the Earth will stop warming if CO_2 emissions reach net zero, an end to warming does not imply an end to climate change. Because the CO_2 not removed by sinks on land and in the ocean remains in the atmosphere for thousands of years, the accumulation of past emissions already makes some impacts inevitable, regardless of future mitigation actions. Certain slow-moving aspects of the climate system such as ice sheets and the deep ocean take decades or centuries to respond to changes. This means that even in a low scenario where global warming slows or stops, some climate changes will continue as the Earth continues to adjust.

Some Ocean Changes Are Locked In Even Under Aggressive Mitigation Scenarios

Past emissions will continue to affect the ocean for thousands of years. Regardless of future emissions, the surface ocean will continue to take up heat from the atmosphere, accumulating 2–4 times as much heat as has been taken up since 1970, even under low or very low scenarios.[79] This heat will have cascading effects on marine ecosystems, increasing the probability of marine heatwaves and causing sea level rise due to the expansion of warm water. Even after the world reaches net-zero emissions, oceans will continue to acidify as they gradually absorb the atmospheric CO_2 produced by past human activities.

Sea Level Will Continue to Rise

Sea level along US coastlines is expected to continue rising regardless of global warming levels for the foreseeable future (at least for hundreds of years). Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2).[67,88] At these short timescales, regional variations in projected sea level rise are large, with 4–12 inches of sea level rise *likely* in the Pacific Northwest and 20–27 inches of sea level rise *likely* in the western Gulf of Mexico. On timescales relevant to infrastructure planning (the design life of infrastructure ranges from 10 to more than 100 years), rates of sea level rise are also expected to continue accelerating under all but the lowest potential global warming levels (greater than 2°C).[67] Future projected changes in sea level will *likely* lead to an increased frequency of coastal flooding events in the continental United States over the next 30 years, with a greater-than-tenfold increase in typically damaging flooding events (e.g., storm surge currently recurring every few years) and a fivefold increase in destructive flooding events (e.g., major storm surge events currently recurring once in many decades) over this time period.[67] The onset of enhanced flooding frequency in coastal areas depends not only on the local trend in sea level but also low-frequency tidal cycles[228] and remote modes of natural climatic variability (e.g., ENSO, the Pacific Decadal Oscillation, and the North Atlantic Oscillation).[229]

Adaptation to a Changing Climate Will Be Necessary

It is not possible to prevent climate change: the current global warming level is already over 1.1°C. The US, across all levels of government, business, and civil society, must both adapt to this reality of a changing climate and prepare for at least some level of additional warming. Inertia in the world's infrastructure[230] and economic and political systems[231] means that the near-term trend in risk over the next few decades is largely independent of the choice of emissions scenario,[224] and the climate benefits of aggressive action to reduce greenhouse gas emissions are unlikely to be realized in the near term. The faster and more extensive the warming, the greater the risk of climate impacts overtaking the speed of adaptation (KM 4.3), as there are both barriers and limits to adaptation (Ch. 31; KM 31.2). This means the US will need to adapt to a changing climate regardless of future emissions.

We Cannot Rule Out Catastrophic Outcomes

Climate Sensitivities Exceeding 4°C Are Unlikely but Not Impossible

There is no known precedent for a species changing its own climate as quickly as humans are changing ours, and there are many uncertainties associated with a rapidly warming world. Low-probability and potentially catastrophic outcomes are not impossible, and these risks persist even under current policies. While recent assessments (KM 3.2)[232] put the *likely* range of equilibrium climate sensitivity—the long-term warming the world will experience if atmospheric CO_2 concentrations are doubled—between 2.5°C and 4.0°C, higher values are not definitively ruled out, and feedback loops such as changes to cloud cover may lead to more warming in the future. Similarly, we cannot rule out a GWL of 4°C or more this century, particularly if climate change strongly reduces the ability of the biosphere or ocean to remove carbon from the atmosphere (Ch. 3).

Changes to the Carbon Cycle May Increase the Amount of CO_2 Remaining in the Atmosphere

Our emerging understanding of land, ocean, coastal, and freshwater systems suggests the possibility of a decline in future carbon uptake capacity among both land and ocean ecosystems.[233,234,235] The balance of carbon uptake and release across terrestrial ecosystems depends on the relative balance of photosynthesis, respiration, and decomposition, which in turn strongly depends on temperature and moisture availability. Changes in either can alter the balance of carbon uptake and release across terrestrial ecosystems (Ch. 7). Similarly, the rate and extent to which atmospheric CO_2 is exchanged with ocean and freshwater systems is controlled by a combination of temperature, salinity, pressure, upwelling, and biological consumption and release of CO_2.

Although net land and ocean carbon sinks have increased in response to increased carbon emissions over the past six decades,[33,233] climate models project that the fraction of emissions taken up by land and oceans will decline, albeit with significant differences in regional responses and underlying mechanisms driving those responses.[1,236] For example, land reservoirs, such as tropical forests or the Arctic–boreal ecosystems, could switch from a net sink to a net source of carbon to the atmosphere (e.g., Huntzinger et al. 2018[234]).

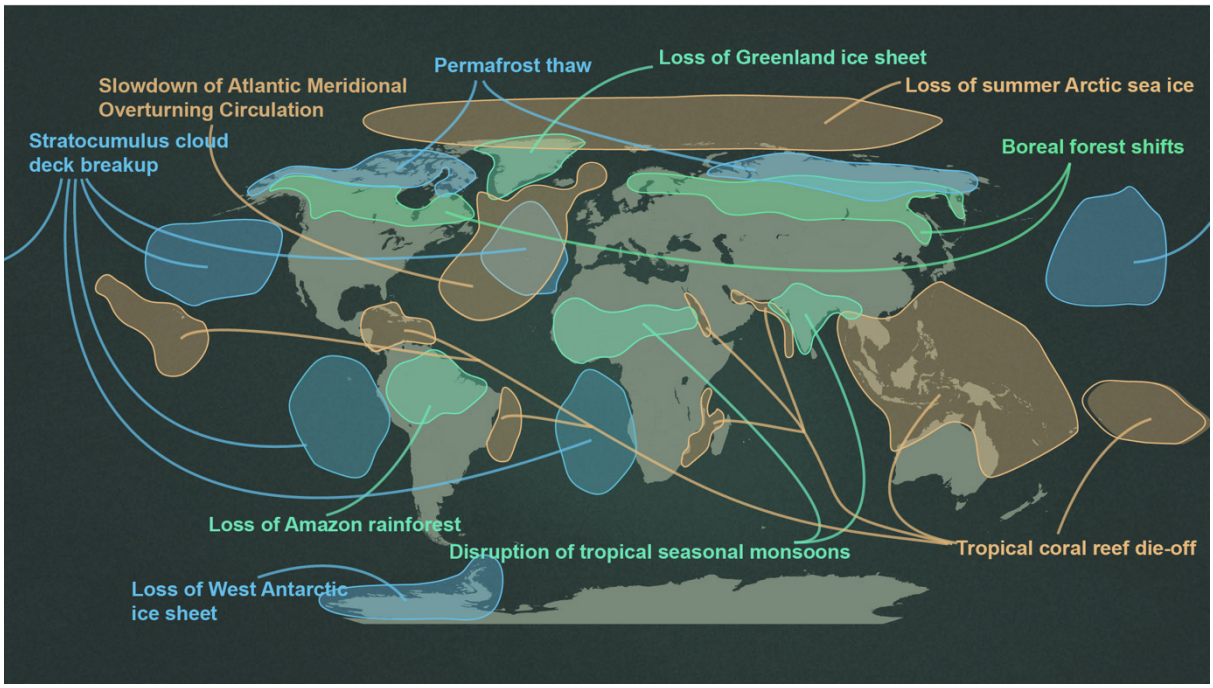
The Arctic–boreal region (Ch. 29) is particularly vulnerable to future climate change and rising temperatures, which could lead to the release of vast amounts of carbon from thawing permafrost, along with changes in vegetation productivity and disturbances such as wildfires and insect outbreaks. There is estimated to be about 4.8–5.9 trillion tons of carbon[237] frozen down to 20 meters in Arctic permafrost. This is roughly double the amount currently in the atmosphere and more than three times what already has been emitted to the atmosphere from fossil fuel use since preindustrial times. With rising temperatures and thawing soils, some of these carbon deposits may be mobilized to the atmosphere, primarily as CO_2. More than one hundred billion tons of CO_2 are *likely* to be released by thawing permafrost over the next century, with higher-end estimates of around 400 billion tons.[238] The total carbon emissions from thawing permafrost are expected to exceed the carbon captured by increases in vegetation productivity.[238] A smaller fraction of permafrost carbon will be emitted as the more powerful greenhouse gas methane. Methane emissions are projected to cause 40%–70% of total permafrost-affected radiative forcing in this century.[239]

Tipping Elements Could Lead to Regional Rapid Changes

Tipping elements, or tipping points as they are colloquially known, are components of the Earth system that may respond to human-caused climate change by transitioning toward substantially different long-term states upon passing key thresholds.[240] In some cases, such changes could produce additional greenhouse gas emissions that could compound global warming.[241,242,243]

Systems that have been identified as possible tipping elements include the slowdown of the Atlantic Meridional Overturning Circulation, Arctic permafrost thaw, loss of the Greenland and West Antarctic ice sheets, Arctic sea ice loss, boreal forest shifts, disruption of tropical seasonal monsoons, Amazon rainforest dieback, tropical coral reef loss, and the disappearance of clouds that currently reflect sunlight cooling the Earth (Figure 2.15).[91] While some of these tipping elements are represented in modern Earth system models, many are still not, and the precise response of these systems to rapid climate change remains poorly understood. It is not possible to say that exceeding a particular GWL will trigger these tipping elements, nor are scientists certain that staying below a particular GWL will prevent them. However, the risk of these nonlinear changes increases with every increment of global warming.

Possible Regional Tipping Elements



Continued warming could push some aspects of the Earth system past tipping points.

Figure 2.15. The figure shows 10 potential tipping elements in the climate system. These include changes to tropical and boreal forests and coral reefs, the loss of Greenland or West Antarctic ice sheets, and changes to the circulation of the oceans and the monsoons. The spatial area affected by each tipping element is shown; colors are used for visual clarity. Adapted with permission from Figure 1 in Wang et al. 2023,[240] which was adapted from McSweeney 2020.[244]

Extreme Sea Level Rise Cannot Be Ruled Out

Increases in sea level along the continental US coast of 3–6 feet by 2100 and 5–12 feet by 2150, depending on human emissions, are distinct possibilities that cannot be ruled out (i.e., they have at least 1% chance of occurrence with global warming levels of 1.5°–4°C).[67,102,210] Beyond 2100, there is still substantial uncertainty in projected sea level rise under the most extreme scenarios of future warming and ice sheet mass loss.[210] This long-term uncertainty is primarily related to persistent gaps in our understanding of how glacier ice flows and fractures,[245,246,247] how snowfall changes under warming,[248] and how melt water behaves on the ice sheet surface.[249,250] Recent progress in better quantifying the uncertainties in the ice sheet contribution to future sea level projections[212,251] and ensuring that models accurately capture past ice sheet behavior[103,252] indicate that ice sheet models are quickly becoming better suited to produce usable and credible sea level projections. Continued model development can reduce uncertainty in the likelihood of extreme sea level rise

scenarios. In particular, there is strong incentive to continue reducing uncertainty surrounding the tail risks associated with potential low-likelihood but high-impact sea level rise projections past 2100, as planning for catastrophic outcomes makes adaptation much more costly.[253,254]

The Biggest Uncertainty Is What We Will Do

Despite uncertainties in how land, ocean, atmosphere, and ice will respond to warming, and despite internal variability in the climate system, the largest source of uncertainty is the trajectory of our greenhouse gas emissions (KM 3.3). This is within human control and depends on our collective policy, economic, and social choices (Ch. 32). Although we probably will not be able to detect climate benefits from even the most aggressive possible emission reductions before the middle of the century, given the magnitude of internal climate variability, there are numerous co-benefits to mitigation in the near term, including improvements to air quality and health, reductions in mortality, and benefits to agriculture, the economy, and the labor market (KM 32.4).[14]

Human efforts to achieve rapid reductions in emissions can still limit global temperature changes to well below 2°C.[222] Global temperatures can be limited to 1.5°C above preindustrial levels by 2100 in scenarios where global CO_2 emissions reach net zero in the middle of this century alongside deep cuts to methane (KM 32.2) and other short-lived climate pollutants, with modest deployments of net-negative emissions thereafter.[255] Most of these scenarios have at least some midcentury temperature overshoot, however, which could result in irreversible consequences to global ecosystems (Ch. 8).[256] Still, the degree to which climate change will continue to worsen is in large part up to humans. The drastic emissions cuts required to stabilize global climate are possible (KM 32.1) and can be achieved in ways that are sustainable, healthy, and fair (KM 32.4). If emissions do not fall rapidly, the risks of extreme weather, compound events, and other climate impacts will continue to grow. How much more the world warms depends on the choices societies make today. The future is in human hands.

Traceable Accounts

Acknowledgments

The authors would like to thank Talia Resnick and Annika Larson for research assistance, including discussions about report structure, literature review, and bibliography management.

Process Description

Most team members were selected from the pool of nominations received via the public call for authors; others were identified through extended networks to ensure diverse representation across multiple axes. The following areas of expertise were identified as crucial for Chapter 2:

- Paleoclimate and long-term context for climate trends
- Carbon cycle observations and greenhouse gases
- Infrastructure and resilience scenarios and projections in the CMIP6 (Coupled Model Intercomparison Project, Phase 6) models
- Regional trends
- Hurricanes, tropical cyclones, and midlatitude storms
- Ocean trends
- Cryosphere and sea level rise
- Climate extremes
- Diverse leadership in science
- Observations of climate trends

Author meetings were held virtually biweekly. Consensus was built by referring to the literature and leveraging the specific expertise of chapter authors. Engagement with other chapters occurred through formal presentations at the April 2022 chapter leadership meeting and one-on-one meetings between chapter lead authors.

Key Message 2.1

Climate Is Changing, and Scientists Understand Why

Description of Evidence Base

The evidence base for human-caused increases in greenhouse gases (GHGs) is extensive and includes satellite and ground-based observations, solid theoretical understanding, and coherent measurements across multiple systems. Evidence for changes in aerosols includes long-term satellite and ground-based observations. Evidence for warming and other long-term climate changes has been extensively documented across multiple variables. Observations at smaller scales are noisier and regional signals more difficult to separate from natural internal climate variability.

Observational surface temperature records are available from a wide variety of scientific groups (e.g., Hansen et al. 2010;[2] Vose et al. 2021;[5] Morice et al. 2021;[3] Rohde and Hausfather 2020[4]). These temperature records combine land surface temperature data from weather stations with ocean sea surface temperature records from sources including ships and buoys. These records are corrected for inhomogeneities

introduced by changes in measurement techniques over time and use various different interpolation techniques to estimate temperature anomalies between measurement locations.

Long-term changes have been observed in many other aspects of the climate system. Seasonal average and extreme precipitation changes are widely documented using observations, and changes are consistent with our physical understanding. The evidence base for ocean changes includes long-term surface and subsurface ocean observations of temperature, salinity, oxygen, and pH in the coastal and open ocean and satellite data.

Paleoclimate evidence includes multiple proxy-based reconstructions and modeling.

Sea level rise over the industrial era has been measured with local tide gauges and satellite altimetry (since the 1970s). Changes in the processes contributing to sea level rise (ocean thermal expansion, glacier and ice sheet melt, and terrestrial freshwater discharges) have been independently measured using in situ techniques in the ocean (e.g., floats, ship-based measurements) and on ice sheets, as well as remotely (e.g., satellite gravimetry and interferometry). Changes in sea ice and lake ice over the past several decades at the poles have been extensively documented from satellites, including visible imagery, altimetry, and microwave backscatter.

Drought has many definitions including meteorological drought, agricultural drought, snow drought, and soil moisture drought; soil moisture projections depend on depth, with surface layers more responsive to short-term temperature changes, while deeper root-zone moisture changes on longer timescales. Moreover, drought can be defined on timescales ranging from several weeks to multidecadal megadroughts. The level of uncertainty in drought changes in several regions depends on the definitions and metrics used and the sources of measurements. Surface-based measurements of soil moisture are limited, and reliable satellite-based measurements of soil moisture are less than a decade long.

Major Uncertainties and Research Gaps

Uncertainty in Global Surface Temperature Reconstructions

In recent years, different groups producing global surface temperature records have somewhat converged in methodological approach, drawing on a larger set of collected weather station data[257,258] and using more granular interpolation approaches rather than simple latitude/longitude grid-cell averaging.[5] Published global surface temperature uncertainties on an annual basis range from ±0.13°C to ±0.2°C in the 1850s when records are more sparse to ±0.03°C to ±0.09°C at present across different surface temperature datasets, with differences between datasets driven by the number of measurements included, the spatial interpolation approach, and the method of uncertainty calculation.[4]

Uncertainty in GHG Emissions Estimates from Inventories and Models

GHG emissions estimates are typically derived using either a "bottom-up" or a "top-down" approach.[259,260] The bottom-up approach uses a combination of activity data and emissions factors alongside empirical or process-based models to estimate the flux exchange between the different compartments of the land–ocean–atmosphere system. A primary advantage of the bottom-up approach is that it allows for explicit characterization of emissions and removals into specific sectors identified in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories.[79,261] However, bottom-up emissions estimates can have significant uncertainty when the activity data or emissions factors are not well quantified or when process-based models are not well characterized due to missing processes or uncertain parameterization. On the other hand, the top-down approach aims to utilize the information from atmospheric greenhouse gas observations and atmospheric transport model to infer information about the distribution of emissions and removals at the surface of the Earth. For example, recent advancements in atmospheric CO_2 observations from satellites and top-down modeling approaches have allowed insights

into CO_2 emissions and removals at the national scale.[262] However, uncertainties in the modeling framework, spatial and temporal observational gaps, and uncertainties in the data may result in large uncertainties in the emissions estimates derived from the top-down approaches. Within the larger carbon cycle science community, various efforts are underway (e.g., REgional Carbon Cycle Assessment and Processes, Phase 2) to increase the level of agreement between estimates from these two approaches, thereby yielding more robust knowledge of GHG emissions.[263]

Uncertainty in Arctic Connections to Midlatitude Weather Extremes

Uncertainties in the influence of the Arctic on midlatitude weather extremes remain due to lack of consistency in model responses and observations, particularly for the winter season. Several advances in the physical understanding of how Arctic processes could influence midlatitude extremes in various seasons have been made since the publication of the Fourth National Climate Assessment,[264] yet the mechanisms continue to be a subject of debate in the scientific community.

Uncertainty in Drought Projections and Definitions

Drought projections are complicated by definitional ambiguity and the use of many standard metrics. For example, there is ambiguity in the definition of "flash drought," with more than 20 unique definitions present in the literature.[265] Moreover, agricultural drought depends not just on precipitation and temperature but also on evaporation and transpiration from the land surface—processes that are projected to change in a warmer world (Ch. 3). Metrics such as the standardized precipitation index or the Palmer Drought Severity Index that rely on meteorological values may yield different projections than indices that take into account land changes (such as precipitation minus evaporation).[266]

Description of Confidence and Likelihood

It is unequivocal that global temperatures are increasing, and scientists are *virtually certain* that the planet has warmed between 1.1° and 1.2°C since the beginning of the industrial revolution, based on multiple observational datasets. There is *very high confidence* that this warming is driven by human-caused GHG emissions, which have increased by over 47% since 1850 based on modeling studies and theoretical understanding. There is *very high confidence* that changes outside the boundaries of the United States affect the Nation's climate because scientists understand the mechanisms by which melting in Antarctica and Greenland affect sea level in the US.[67] The links between tropical warming and atmospheric river intensity are due to well-understood atmospheric thermodynamics.[98,99] A wide range of detection and attribution studies (discussed in Ch. 3 and summarized in Eyring et al. 2021[267]) establish that long-term changes due to climate change have been observed in many aspects of the climate system.

Key Message 2.2

Extreme Events Are Becoming More Frequent and Severe

Description of Evidence Base

Extreme events are rare by definition, but multiple datasets[125,268] indicate they are increasing. The authors have a solid theoretical understanding of how some events (heatwaves, downpours) should increase in a warming world (Ch. 3). Others (e.g., agricultural drought) depend on multiple interacting physical processes.[190,269] Event attribution now allows us to assign a quantifiable fraction of attributable risk to climate change (Ch. 3).

A wide variety of observational evidence exists for the occurrence of different storm types. Trained weather observers and storm spotters create storm reports across the country for severe hail, winds, and tornadoes. The National Weather Service (NWS) WSR-88D radar network maintains nationwide surveillance observations of precipitation, winds, and storm occurrence. The NWS additionally conducts storm damage surveys for high-impact events. NOAA and Air Force Hurricane Hunters conduct surveillance flights into tropical cyclones expected to impact US interests. NOAA geostationary satellite observations maintain a record of cloud properties and lightning occurrence. However, the length and representativeness of each data source are variable; storm reporting relates to population density and exposure, and the availability of trained observers impacts record quality, especially for transient phenomena such as hail.

Major Uncertainties and Research Gaps

There is growing evidence that the impacts of climate change are, and will be, distributed unequally across US populations due to differences in both exposure and vulnerability. However, there are gaps in understanding the community-level impacts of projected changes in extreme events. Vulnerability at this level is in part a function of our investments (capital, operations, and management) in the built environment and natural resource functionality that serve to buffer these impacts (e.g., stormwater conveyance and levees to reduce flooding, water storage to relieve water shortages during drought). There is a lack of systematic assessment of these assets and other facets of vulnerability across the United States.

New literature has emerged documenting changes in certain types of compounding extremes such as heat and drought, but the limited observed record hinders quantifying long-term trends in several other compound extremes. Several frameworks for studying various compound extremes have emerged as well, and the physical understanding of certain compound extreme events such as heat/drought, heat/humidity, and coastal wind/precipitation/flooding has been documented, yet the understanding of the physical drivers of many other compound extremes is still emerging. Therefore, there are gaps in methodological advances, advances in understanding of their physical drivers, and studies quantifying projections in compound extreme risks.

The lack of homogenized daily and hourly temperature datasets limits our ability to reliably assess the evolution of extreme heat events over century-scale periods, although the availability of modern reanalysis products has increased agreement in changes in extreme heat events over the past 50 years.

There is limited research on changes in lightning activity due to lack of a long-term observational record. Satellite-based records and lightning detection networks are not sufficiently long to allow for detecting trends. Lightning can pose major hazards to society including direct casualties, igniting wildfires, and damaging energy infrastructure.[167]

Description of Confidence and Likelihood

There is *very high confidence* that heatwaves globally are becoming more frequent and severe, based on multiple observational datasets. In the United States, there is *high confidence* that heatwaves in the West are becoming more common and severe based on observational records since 1901 (Figure 2.7). There is also *very high confidence* that climate change is and will continue to make rainfall extremes more intense. Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have *high confidence* that storms are delivering more rainfall and *high confidence* that storm surges are becoming higher. There is *very high confidence* that the Southwest is experiencing more severe drought: a recent paper found the 2002–2022 multidecadal soil moisture drought was the worst in the past 1,200 years.[135] The eastern region is experiencing reduced drought risk; studies suggest a transition toward more frequent extremes[141] and indicate that warming may partially counteract the effects of increased precipitation. Other extremes involve more complex interactions between human and natural systems: the occurrence and impacts of wildfires depend on fire ignition and suppression practices. However, while fire risk is not solely determined by climate factors, the authors have *very high confidence* that the hot and dry weather conditions that elevate fire risk are becoming more common.

Key Message 2.3

How Much the Climate Changes Depends on the Choices Made Now

Description of Evidence Base

The Shared Socioeconomic Pathways (SSPs) were made available to the broader research community, replacing the old Representative Concentration Pathways (RCPs) and providing a more detailed assessment of the range of possible emissions pathways, as well as mitigation and adaptation challenges across different sets of socioeconomic assumptions.[270] A subset of the SSPs served as the basis for CMIP6 scenarios used in this Assessment and the Sixth Assessment Report (AR6) of the IPCC.[88]

CMIP6 provides a large set of model runs to use in evaluating different future emissions pathways and global warming levels. In addition, recent work assessing multiple lines of evidence from observational data, paleoclimate evidence, and physical process modeling has helped narrow the range of climate sensitivity.[232] The IPCC AR6 produced a new set of assessed warming projections based on these climate sensitivity estimates and CMIP6 models that were weighted based on their performance in reproducing historical temperatures.

The IPCC AR6 Working Group III[256] report explored a wider range of "overshoot" scenarios, where global temperatures temporarily exceed 1.5°C before being reduced through the large-scale use of negative-emissions technologies. Additionally, AR6 Working Group I provided a thorough exploration of the zero-emissions commitment associated with the cessation of carbon dioxide (CO_2) and other GHG emissions, building off the work of the Zero Emissions Commitment Model Intercomparison Project (ZECMIP).[227]

Recent literature summarized in IPCC AR6 Working Group III[256] and in Hausfather and Moore (2022)[219] provides a clearer sense of expected global average surface temperature outcomes under scenarios including only current policy, near-term 2030 commitments, and long-term net-zero commitments.

Major Uncertainties and Research Gaps

Major uncertainties remain surrounding the emissions trajectories implied by current policies and the plausibility of worse-than-current-policy emissions outcomes. While most current policy scenarios in the literature project relatively flat global emissions over the next few decades, there are some (e.g., in the IPCC AR6 Working Group III scenario database) in which emissions continue to increase. Similarly, large uncer-

tainties remain when translating near-term and long-term mitigation commitments to global emissions pathways, particularly for non-CO_2 GHGs and other climate forcings like aerosols.

The translation from emissions scenarios to warming outcomes is complicated by uncertainties in both the sensitivity of the climate to emissions (both the transient climate response and the equilibrium climate sensitivity) and carbon cycle feedbacks that may affect the portion of emissions that accumulate in the atmosphere. Specifically for carbon cycle feedbacks, it will be the balance between the response of land and ocean systems to future climate that will determine the strength and extent of carbon uptake by these systems, whether they may become a net source of CO_2 to the atmosphere, and, consequently, the trajectory of future GHG forcings.

While recent work[232] has meaningfully narrowed the potential range of climate sensitivity, there are still tail risks of outcomes where equilibrium climate sensitivity exceeds 5°C or is below 2°C per doubling of atmospheric CO_2. There is also disagreement between a subset of high-sensitivity CMIP6 models and other lines of evidence supporting a narrower range of climate sensitivity.[271]

On timescales of less than 50 years, the most significant uncertainties in future sea level are due to regional and local variations in sea level rise and the interannual sea level variability intrinsic to the coastal ocean system. In Alaska and New England, the regional gravitational influence of glaciers and ice sheets may cause lower sea level rise or even sea level fall in the future, although the extent of these gravitational effects is highly dependent on the spatial fingerprint of glacier and ice sheet loss, which is uncertain.[100] Internal variability and human-caused changes in ocean circulation appear to have a strong effect on year-to-year sea level, particularly in the US Mid-Atlantic Coast,[272] but are not consistently simulated between models or included in the range of uncertainty in most sea level projections.[67]

On longer timescales (2100 and beyond), there are substantial uncertainties in projected sea level rise due to an incomplete understanding (and intermodel differences) of how the Greenland and Antarctic ice sheets will behave in a warmer climate. There is a consensus that past carbon emissions and even relatively moderate future global warming levels commit the planet to at least 3–6 feet of sea level rise over hundreds to thousands of years from the melting of the Greenland and Antarctic ice sheets.[273] However, there are many feet of uncertainty remaining both in the already-committed sea level rise and the sea level rise that could be expected under a range of global warming levels.[102,210,274,275] Ongoing research to understand how glaciers and ice sheets flow, fracture, and melt in response to climate change aims to narrow this wide range in sea level rise beyond 2100.

Projections of seasonal and extreme precipitation are widely studied and show more consistent and robust responses in extremes than average changes. The physical process link between higher temperatures and higher moisture availability in the atmosphere is well documented and understood. However, uncertainties remain in our understanding of the response of precipitation-producing systems, particularly those governed by mesoscale processes such as mesoscale convective systems and thunderstorms, which are not directly simulated in global climate models. Uncertainties, especially around how other factors that influence storm development (such as vertical wind shear and atmospheric instability) will change in future climates, link back to model uncertainty and bias at larger scales.

Uncertainty in drought projections arises from these uncertainties in precipitation. Climate models generally project drying in the US Southwest in response to elevated global warming levels, but the precipitation response is highly uncertain. The response of land vegetation also complicates drought projections. Under elevated CO_2 levels, certain types of plants may become more efficient at using water due to a physiological response. This is expected to be at least partially counteracted by greening in response to elevated CO_2 levels. Additionally, the vegetation response to increased heat stress, extreme precipitation, and fire risk is complex and not yet fully understood.

Description of Confidence and Likelihood

There is *very high confidence* that many impacts—both changes to the average state and the risk of extreme events—will intensify as the temperature increases. This is based on physical understanding of the underlying drivers reflected in climate models of varying complexity, including the state-of-the-art general circulation models participating in CMIP6.[276] It is an unequivocal fact, backed by over 100 years of theory and observation, that warming increases with GHG emissions,[277] and warming is *virtually certain* to continue at current levels of emissions. There is *very high confidence* that warming will continue at least until emissions of carbon dioxide reach net zero. The cessation of warming at the point of (net) zero CO_2 emissions (called the zero-emissions commitment, or ZEC) traces back to Matthews and Caldeira (2008),[278] Solomon et al. (2009),[279] and Matthews and Weaver (2010),[280] who were among the first to explore zero-emissions scenarios in emissions-driven climate model runs. The common conflation of constant concentration scenarios with zero-emissions scenarios has led to the misconception that substantial future warming is inevitable. In the lead-up to AR6, there was a desire by the community to further explore the robustness of ZEC results. This led to the creation of ZECMIP, where 18 different Earth system models were used to examine ZEC under a variety of emissions-reduction pathways and cumulative emissions scenarios. ZECMIP broadly found that ZEC was 0°C ± 0.3°C across the Earth system models examined.[227] Hence, rapidly reducing emissions would *very likely* limit future warming (*very high confidence*). It is *very likely* that the eventual global warming in response to a doubling of atmospheric CO_2 is between 2.3° and 4.7°C and *likely* that the warming would be between 2.6° and 3.9°C.[232] There is *high confidence* that catastrophic scenarios where warming exceeds 4°C cannot be ruled out due to uncertainties in climate sensitivity, carbon cycle feedbacks,[239,281] and emissions scenarios.[282]

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Fifth National Climate Assessment: Chapter 3

Earth Systems Processes



Chapter 3. Earth Systems Processes

Authors and Contributors

Federal Coordinating Lead Author

Adam Terando, US Geological Survey

Chapter Lead Author

L. Ruby Leung, Pacific Northwest National Laboratory

Agency Chapter Lead Authors

Renu Joseph, US Department of Energy

George Tselioudis, NASA Goddard Institute for Space Studies

Chapter Authors

Lori M. Bruhwiler, NOAA Global Monitoring Laboratory

Benjamin Cook, NASA Goddard Institute for Space Studies

Clara Deser, National Center for Atmospheric Research

Alex Hall, University of California, Los Angeles

Benjamin D. Hamlington, NASA Jet Propulsion Laboratory

Andrew Hoell, NOAA Physical Sciences Laboratory

Forrest M. Hoffman, Oak Ridge National Laboratory

Stephen Klein, Lawrence Livermore National Laboratory

Vaishali Naik, NOAA Geophysical Fluid Dynamics Laboratory

Angeline G. Pendergrass, Cornell University

Claudia Tebaldi, Pacific Northwest National Laboratory

Paul A. Ullrich, University of California, Davis

Michael F. Wehner, Lawrence Berkeley National Laboratory

Technical Contributors

Flavio Lehner, Cornell University

Adam S. Phillips, National Center for Atmospheric Research

Review Editor

Gavin Schmidt, National Aeronautics and Space Administration

Cover Art

Ian van Coller

Recommended Citation

Leung, L.R., A. Terando, R. Joseph, G. Tselioudis, L.M. Bruhwiler, B. Cook, C. Deser, A. Hall, B.D. Hamlington, A. Hoell, F.M. Hoffman, S. Klein, V. Naik, A.G. Pendergrass, C. Tebaldi, P.A. Ullrich, and M.F. Wehner, 2023: Ch. 3. Earth systems processes. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH3

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Introduction

The Earth system consists of the atmosphere, land, oceans, and cryosphere, which interact and cycle energy, water, and essential elements of life such as carbon, nitrogen, and phosphorus. Powered by the sun, these interactions and cycles determine Earth's climate, which naturally varies at a broad range of timescales from days to millennia through diverse Earth system processes.

Since industrialization, human activities have dramatically altered atmospheric composition and land cover, with consequential impacts on climate. Human-caused emissions of greenhouse gases have warmed the planet by trapping more outgoing energy, leading to a change in the net energy balance at the top of the atmosphere. The net increase in energy input warms the surface and the air and increases moisture in the lower atmosphere, resulting in significant changes in Earth system processes, including changes in atmospheric and oceanic circulations, clouds, and precipitation and melting of sea ice, glaciers, and ice sheets. The increase in energy input also provides fuel for increasing the frequency and intensity of extreme weather events such as heatwaves and convective storms.

In recent years, advances have been made in understanding the changes that have already occurred, attributing changes to human influence, and projecting future changes. These advances are facilitated by new and diverse observations, improved models and experiments, and the combination of observations and models to support multiple lines of evidence and inquiry. Building on previous scientific assessments, these advances have enabled scientists to unequivocally attribute the observed global warming to human activities and to narrow by 50% the range of estimated global warming that would be caused by a doubling of atmospheric carbon dioxide concentration. Complementary to Chapter 2, which focuses on past and future climate trends, particularly in the US, this chapter discusses more generally how Earth system processes respond to the drivers of climate change. It begins by introducing the natural and human (anthropogenic) drivers of climate change (KM 3.1). Next, it addresses our understanding of the climate response to those drivers, including the sensitivity of the climate to changing greenhouse gas concentrations and the feedback processes that can amplify or partially counteract the influences of human activities (KM 3.2). Recent advances in observations, modeling, and attribution of climate change are then discussed (KM 3.3). Lastly, changes in Earth system processes that underpin the many facets of global and regional climate change (KM 3.4) and changes in extreme events (KM 3.5) are discussed.

Key Message 3.1

Human Activities Have Caused the Observed Global Warming

Human activities—primarily emissions of greenhouse gases from fossil fuel use—have unequivocally caused the global warming observed over the industrial era. Changes in natural climate drivers had globally small and regionally variable long-term effects over that period.

Shifts in climate at the global scale occur primarily in response to processes that change the balance between incoming solar energy and the outgoing energy radiated from Earth at the top of the atmosphere (TOA). The drivers of change are both natural and human-caused and may be transient or long-lived. Changes in TOA net radiation balance resulting from a perturbation in climate drivers can be quantified in terms of the effective radiative forcing (ERF), measured in units of watts per square meter (W/m^2). The main natural drivers of climate change—variations in solar radiation and volcanic aerosols—have negligible contributions to long-term climate forcing.[1,2] Warming from fossil fuel emissions of carbon dioxide (CO_2) is expected to last centuries to millennia, because of the slow rate of the natural processes that remove CO_2

from the atmosphere. Changes in climate may be further amplified or diminished through feedbacks in the climate system. Feedbacks are processes changed by the warming that then modify the TOA radiation balance and the overall level of warming. In the surface–albedo feedback, for example, warming melts ice cover over the land and ocean, exposing darker surfaces beneath that absorb more energy rather than reflecting it, contributing to further warming. See Chapter 2 of the Climate Science Special Report[3] for further details on emissions sources, radiative forcing, and ERF.

Anthropogenic Drivers

Well-Mixed Greenhouse Gases

Since the release of the Fourth National Climate Assessment (NCA4) in 2018, global atmospheric abundances of the main well-mixed greenhouse gases (WMGHGs), including CO_2, methane (CH_4), and nitrous oxide (N_2O), have continued to increase (KM 2.1). Atmospheric abundances of halogenated gases have also changed, some increasing and some decreasing due to ozone-depletion policies. Preindustrial to present-day (1750–2019) increases in WMGHG concentrations contributed the bulk of the total human-caused forcing, with increases in CO_2 contributing an ERF of 2.16 ± 0.26 W/m^2, followed by 0.54 ± 0.11 W/m^2 from CH_4, 0.41 ± 0.08 W/m^2 from halogenated compounds, and 0.21 ± 0.03 W/m^2 from N_2O.[2] The ERF due to changes in CH_4 abundance is lower than that due to changes in emissions because of offsetting effects of other chemical constituents as discussed below.

The growth in global atmospheric CO_2 levels since 1750 was primarily driven by direct emissions from human activities such as fossil fuel combustion, cement manufacturing, and land-use change. About 41% ± 11% of the 700 ± 75 PgC of CO_2 (1PgC = 1 billion metric tons of carbon [GtC]) emissions between 1750 and 2019 remain in the atmosphere today, with the rest absorbed by oceans and the land biosphere.[4]

Methane is considered both a WMGHG and a short-lived climate forcer due to its chemical reactivity and an approximate 10-year atmospheric lifetime. Methane is produced by both natural processes and human activities. Observational evidence points to microbial sources (agriculture, waste, and natural wetlands) as the predominant cause of the observed increase in global growth in atmospheric CH_4 since 2006,[5,6] with a smaller contribution from fossil fuel production.

In addition to its direct effect on radiative forcing, CH_4 also has an indirect influence through its chemical effects on other climate drivers, including CO_2, ozone, stratospheric water vapor, aerosols, and halogenated gases.[7] This leads to an increased effect of CH_4 on the amount of energy trapped in the Earth system. Over 20 and 100 years, a given mass of CH_4 emissions is about 80 and 30 times, respectively, more efficient at trapping energy in the climate system than the same emitted mass of CO_2.[2] This comparison of energy trapped due to a given mass of emitted gas compared to the same emitted mass of CO_2 is known as the global warming potential (GWP), and it is always specified for a given time horizon due to the varying chemical lifetimes of non-CO_2 greenhouse gases. For CH_4, the 100-year GWP is about 30 (relative to a GWP for CO_2 being, by definition, equal to 1 over the same 100-year period).

The increase in atmospheric N_2O levels since 1750 is small compared to that of CO_2 and CH_4, although rates have increased in recent years due to increased nitrogen fertilizer use in agriculture.[8] Nitrous oxide has an atmospheric lifetime of about 116 years and is nearly 300 times more efficient at trapping energy than CO_2 over a 100-year period.[9]

Many halogenated compounds, which are primarily manufactured gases, also contribute to climate change. These include chlorofluorocarbons (CFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), with lifetimes of decades to millennia, and hydrogen-containing halogenated compounds like hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), with lifetimes of months to decades. The atmospheric abundances of most CFCs have continued to decline in response to regulations under the Montreal

Protocol on Substances that Deplete the Ozone Layer and its amendments.[10] Atmospheric levels of HFCs are increasing, while the rates of atmospheric growth of major HCFCs have slowed down in recent years.

Non-methane Short-Lived Climate Forcers

Short-lived climate forcers (SLCFs) are chemically reactive in the troposphere (lower atmosphere), with atmospheric lifetimes typically shorter than two decades, and include ozone, aerosols, and methane. Most SLCFs are also air pollutants or precursors for air pollution (see KM 14.5). An assessment of the ERF effects for two primary non-methane SLCFs are given below.

Ozone: Ozone is a greenhouse gas that occurs naturally throughout the atmosphere and is a harmful air pollutant near the surface (KM 14.1). It is formed in the atmosphere through chemical reactions involving sunlight: in the stratosphere, ozone production occurs via chemical reactions involving the breakdown of oxygen molecules by sunlight, while in the troposphere, it is produced by chemical reactions involving emissions of methane, nitrogen oxides (nitric oxide and nitrogen dioxide), carbon monoxide, and non-methane volatile organic compounds in the presence of sunlight. Increases in human-caused emissions of these precursors since preindustrial times are responsible for increases in tropospheric ozone.[7,11] In the stratosphere, increases in human-caused halogenated ozone-depleting substances (ODSs) have contributed to declining ozone abundances. Over the period 2000–2017, stratospheric ozone concentrations have increased slightly in response to declining ODSs because of the Montreal Protocol and its amendments.[10] The combined changes in tropospheric and stratospheric ozone from the preindustrial era to the present have had an overall warming effect of 0.47 ± 0.23 W/m^2, with a smaller contribution from stratospheric ozone changes.[2]

Aerosols: Aerosols are small particles that are emitted directly from human activities and natural processes and are also formed in the atmosphere via reactions involving gaseous precursor emissions. Ice core records indicate that aerosol concentrations increased from the preindustrial era until the 1970s and 1980s, driven by northern midlatitude emissions, and declined thereafter.[10] This decline is attributed to reductions in emissions from Europe and North America due to air quality regulations. Satellite data and ground-based records over the modern period confirm the decline in aerosol concentrations over the northern midlatitude and Southern Hemisphere continents but show increases over South Asia and East Africa.[10,12] Globally, aerosol concentrations have been declining since 2000, driven by reductions in some regions. Aerosols from human activities are also air pollutants (KMs 14.1, 2.1) and influence Earth's radiation balance directly by scattering or absorbing solar radiation, through interactions between aerosols and clouds, and by changing the surface reflectivity when light-absorbing aerosols are deposited on snow and ice. Changes in aerosols over the period 1750–2014 have had an overall cooling effect of –1.3 ± 0.7 W/m^2.[2] Since NCA4, the uncertainty in total aerosol ERF has been reduced, and it is now *virtually certain* that the total aerosol ERF is negative, as discussed in the Technical Summary of the Working Group I contribution to the Intergovernmental Panel on Climate Change Sixth Assessment Report.[13]

Land-Use Effects on Surface Albedo

Anthropogenic water storage, agricultural practices, and forest cover changes modify the land surface and alter the surface energy balance. Increased water storage on land reduces surface reflectivity and has a localized cooling effect due to evaporation. Irrigation of crops has a similar localized cooling effect through both increased evaporation and plant transpiration.[14] Forests can induce warming because they absorb surface energy or induce cooling because of transpiration.[15] Deforestation can cause cooling by brightening the surface and increasing ground evaporation, but it may also cause warming by reducing ground shading and plant transpiration.[16] Overall, global changes in land use have contributed a net negative ERF (cooling effect) of –0.20 ± 0.10 W/m^2.[2]

Natural Drivers

Solar Irradiance

Climate forcing from changes in solar irradiance are small relative to changes in anthropogenic greenhouse gases over the industrial era. Changes in solar irradiance over the period 1750–2019 have contributed an ERF of 0.01± 0.07 W m^{-2}.[2]

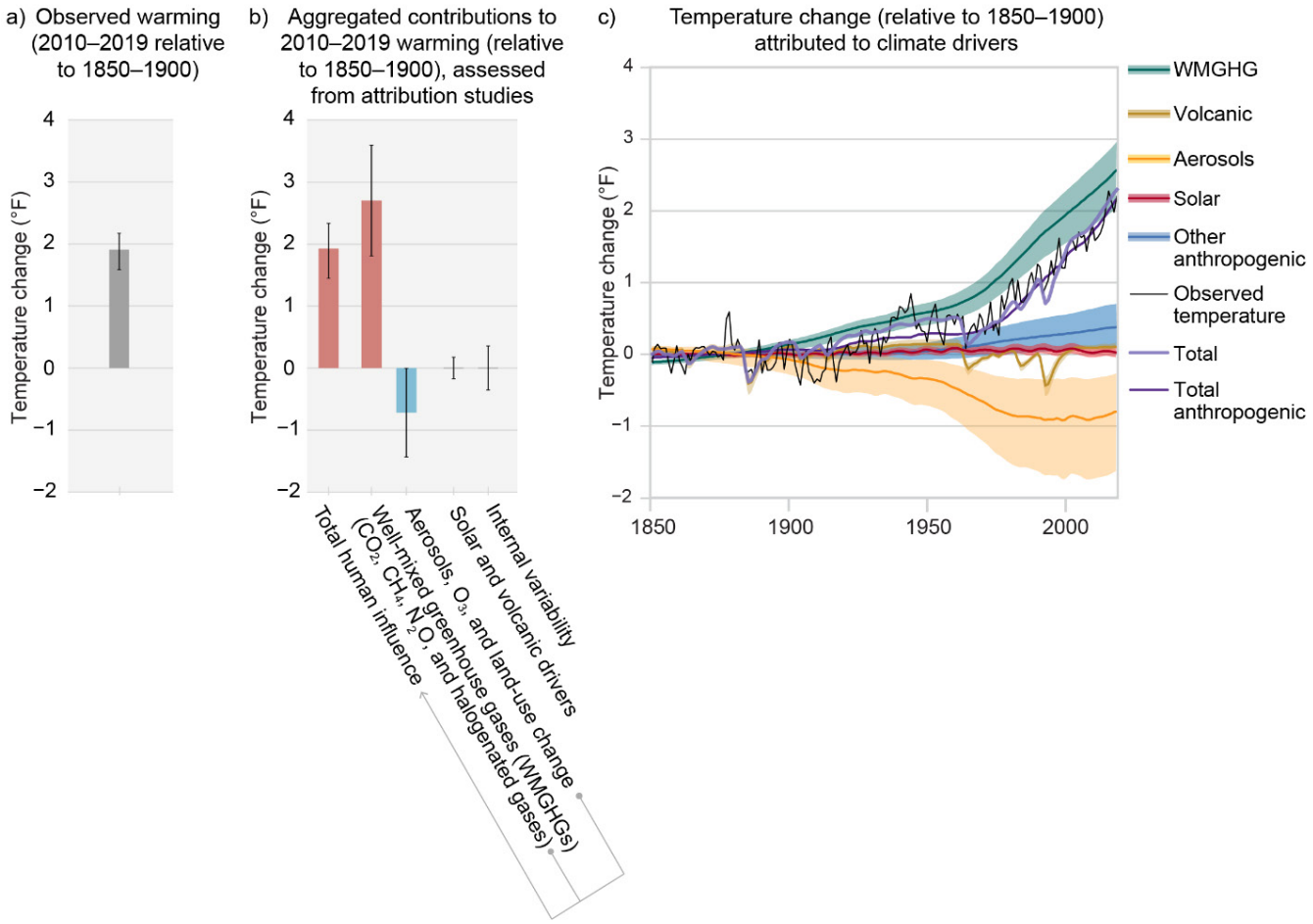
Volcanic Aerosols

Sulfate aerosols formed in the stratosphere from injections of sulfur dioxide (SO_2) from explosive, episodic volcanic eruptions and more frequent smaller eruptions reduce incoming solar radiation and lead to a cooling effect. Volcanic aerosols can also trigger changes in upper-tropospheric clouds, leading to warming,[17,18] although the magnitude of this effect is highly uncertain.[19] Quantitative assessment of the net ERF over the industrial era for volcanic aerosols shows negligible effects on the long-term temperature trends.

Global Surface Temperature Response to Climate Drivers

A notable recent advance is the quantification of the contributions to global surface air temperature change over the preindustrial to present-day period due to forcings from changes in different climate drivers.[2] Panels a and b in Figure 3.1 show that observed warming in 2010–2019 (compared to 1850–1900) is dominated by contributions from WMGHGs and ozone. This warming has been partially counteracted by the cooling effect from aerosols and land-use change. Because of declining aerosols, the global aerosol cooling effect has weakened since about 1980, and the rate of global warming has increased, mainly due to increasing greenhouse gases (Figure 3.1c). The aerosol cooling effect has a strong regional dependence,[7] contributing to differences in regional climate change (KM 3.4). Natural drivers over the historical period have contributed a small, highly variable cooling effect. Uncertainties in the ERF values, especially of aerosols, contribute to uncertainty in the attribution of observed warming.

Observed Global Warming and Attribution to Climate Drivers



The warming observed over the industrial era was driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling.

Figure 3.1. The figure shows (**a**) observed change in global average surface temperature in 2010–2019 relative to 1850–1900; (**b**) temperature change over the same period (also relative to 1850–1900) attributed to total human influence, including changes in well-mixed greenhouse gas concentrations (including carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], and halogenated gases); combined changes in aerosols, ozone (O_3), and land use (land-use reflectance); and solar and volcanic drivers and natural climate variability; and (**c**) time evolution of observed temperature (2010–2019, relative to 1850–1900; black line) attributed to different climate drivers from 1850 to 2019, as well as total human influence ("Total anthropogenic"; purple line) and combined natural and human influence ("Total"; lavender line). Whiskers in (a) and (b) show the *very likely* range, while shaded uncertainty bands in (c) show *very likely* (5%–95%) ranges. Note that in (b), the warming effect of ozone is largely offset by the cooling effect of aerosols, resulting in a net cooling when the effects of aerosols, ozone, and land-use change are combined. (a, b) Adapted with permission from Figure SPM.2 in IPCC 2021;[20] (c) adapted with permission from Figure 7.8 in Forster et al. 2021[2] and Figure 2.11c in Gulev et al. 2021.[10]

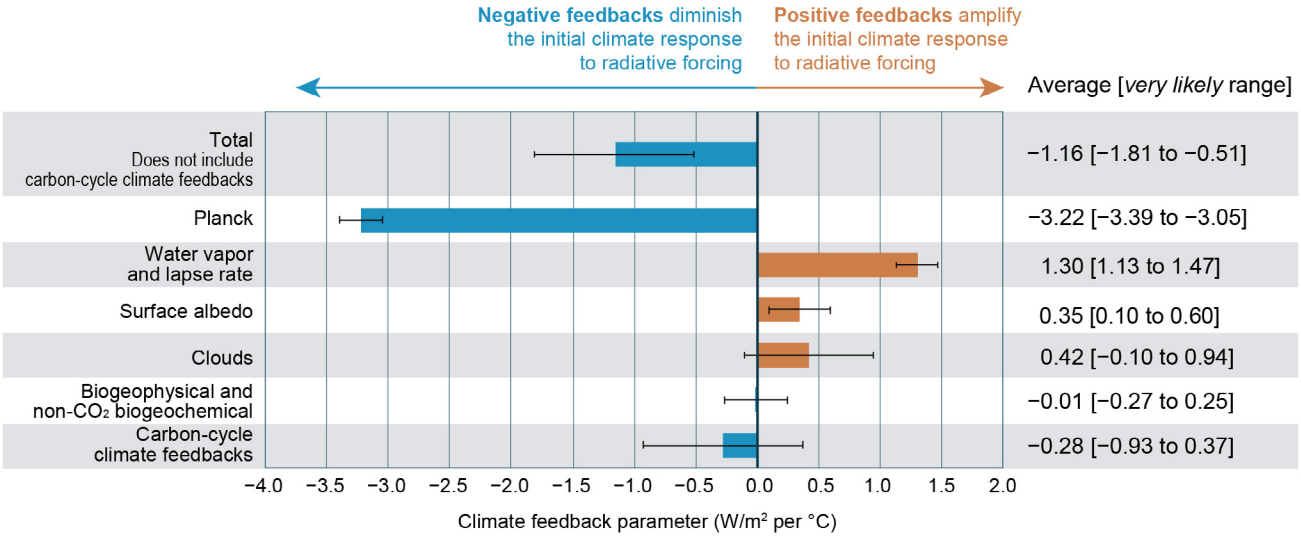
Key Message 3.2

The Estimated Range of Climate Sensitivity Has Narrowed by 50%

Recent improvements in the understanding of how climate feedbacks vary across timescales have narrowed the estimated *likely* range of warming expected from a doubling of atmospheric carbon dioxide by 50% to between 4.5°F and 7.2°F (*high confidence*).

The total climate response for a given forcing is an important indicator of the expected climate change impacts. This response is commonly characterized by the equilibrium climate sensitivity (ECS), defined as the change in global average surface temperature after the climate system reaches a steady state following a doubling of the atmospheric CO_2 concentration. A larger value of ECS indicates larger increases in global warming for a given increase in greenhouse gases. ECS depends both on the ERF from a doubling of CO_2 and the sum of climate feedbacks that can either amplify (a positive feedback) or dampen (a negative feedback) the temperature change. The primary feedbacks arise from increased emissions of longwave radiation that cools the warmer planet (Planck feedback); increases in atmospheric water vapor (a greenhouse gas); changes in the vertical profile of atmospheric temperature; reductions in the surface area covered by reflective snow and ice; and changes in cloudiness. Cloud feedbacks are the largest source of ECS uncertainty (Figure 3.2).[2,21] The response of the carbon cycle to climate warming contributes additional uncertainty (KM 3.4).

Feedbacks in the Climate System

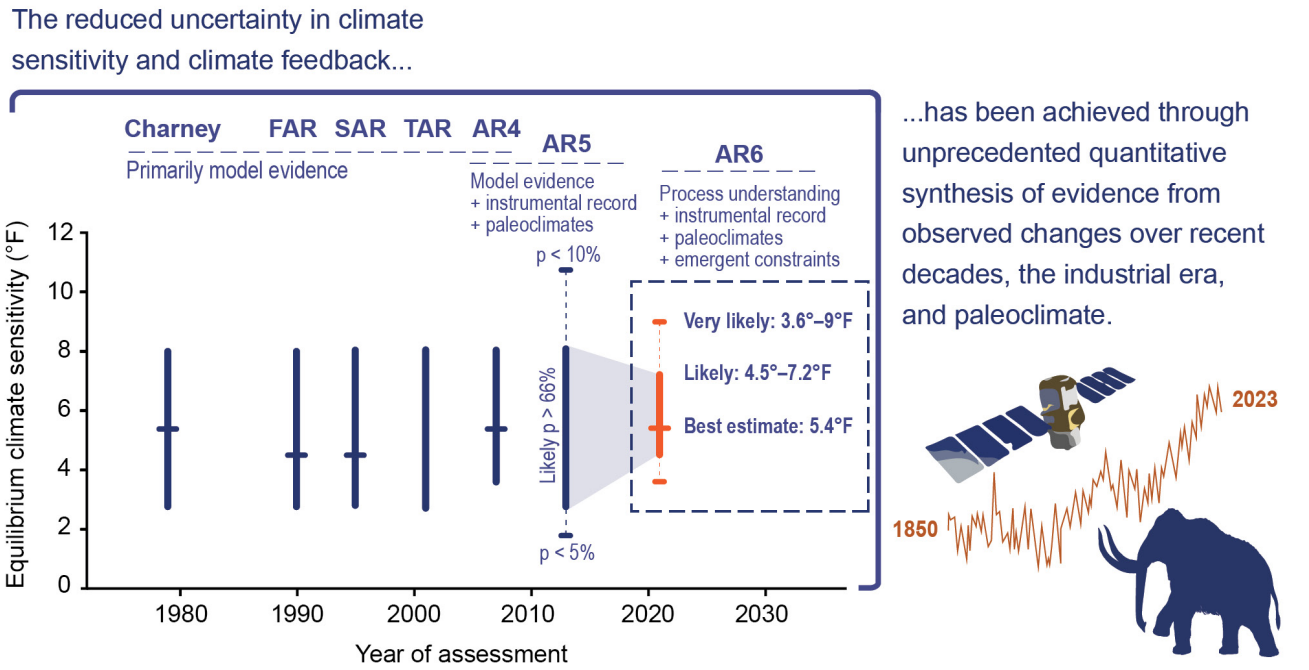


Multiple feedback processes in the climate system amplify or partially diminish the response to radiative forcing; quantifying their values is necessary to determine the climate response to human activities.

Figure 3.2. The graph shows assessed values of feedbacks acting in the climate system. The total feedback is the feedback that contributes to the assessed value of climate sensitivity. Bars denote the average feedback values, and uncertainties denoted by whiskers represent *very likely* ranges. Negative feedbacks are denoted by blue bars and positive feedbacks by orange bars. The feedback values are estimated by climate models based on the equilibrium change in Earth's energy balance in response to a doubling of carbon dioxide (CO_2) with and without the feedback processes. W/m^2 is watts per square meter. Adapted with permission from Figure TS.17 in Arias et al. 2021.[13]

The key development since NCA4 is that the ECS uncertainty range has narrowed.[2,21] Recent assessments place ECS between 4.5°F and 7.2°F (2.5°C and 4.0°C), a 50% uncertainty reduction from previous assessments (Figure 3.3). It is *virtually certain* that ECS is greater than 2.7°F (1.5°C), guaranteeing significant climate change impacts from ongoing increases in CO_2 and other greenhouse gases.

Advances in Understanding Climate Sensitivity and Climate Feedback



Uncertainties in climate sensitivity and feedbacks have been reduced by synthesizing multiple lines of evidence.

Figure 3.3. The graph (**left**) shows estimates of equilibrium climate sensitivity (ECS; y-axis) and the considered lines of evidence as a function of the years (x-axis) in which various assessment reports were released. These assessments include the "Charney Report"—a study by an ad hoc US research group that was published in 1979—and the first through sixth assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC), indicated here by the acronyms FAR, SAR, TAR, AR4, AR5, and AR6, respectively. NCA adopts the climate sensitivity values assessed by IPCC reports. Thick vertical bars indicate the *likely* range, and the horizontal tick marks on these bars, where present, indicate the best estimate (tick marks for the AR5 indicate a less than 5% probability of ECS being below 1.8°F and less than 10% probability of being greater than 10.8°F). The reduced estimated range of ECS in AR6 reflects advances in understanding of how climate feedbacks operate across timescales and an improved ability to combine physical constraints with observational data from recent decades, the industrial era, and paleoclimate records. The images of a satellite, the surface temperature time series, and a woolly mammoth (**right**) are emblematic of these three lines of evidence used to assess climate sensitivity. Adapted with permission from Figure TS.16a in Arias et al. 2021.[13]

This uncertainty reduction results from advances in combining observations and targeted modeling results from nearly independent lines of evidence, each of which generally agrees on the values of ECS. The lines of evidence include 1) observed present-day variations on monthly to interannual timescales from which cloud and other climate feedbacks are inferred; 2) observed temperature changes between the preindustrial period and present and associated relationships to ERF; and 3) estimated temperature and radiative forcing changes for multiple warm and cold periods in paleoclimate records.[21]

Advances since NCA4 include the following:

- Increased use of present-day observations to determine cloud and other climate feedbacks. Confidence in inferring feedbacks for centennial-scale climate changes from present-day variations on monthly to interannual timescales is bolstered by "emergent constraints" found in Coupled Model Intercomparison Project (CMIP) model ensembles (see App. 3).
- Increased use of very-high-resolution cloud-resolving models to determine expected changes in response to the warmer conditions
- Greater understanding of how changes in the spatial distribution of sea surface temperature over the historical period affected climate feedbacks
- Greater availability of reconstructed temperatures and ERF values for paleoclimate and greater confidence in how to account for the state-dependence of climate feedbacks and departures from equilibrium

The reduction of uncertainty in ECS was accompanied by reduced uncertainty in the cloud feedback. There is greater confidence that the sum of feedbacks over all cloud types is positive (i.e., a warming effect) and primarily results from increases in the altitude of high-level clouds and decreases in the amount of marine stratocumulus and continental low-level clouds. A previously identified negative feedback arising from the transition of cloud phase from ice to liquid as the planet warms[22] is now thought to be substantially smaller based on new observational evidence.[23,24]

Importantly, the new assessed range of ECS relies on observational analyses and selected modeling evidence but does not consider the ECS values from climate models directly. Models with ECS values outside of the assessed range are thought to have *unlikely* values of ECS. In particular, the CMIP6 models with ECS values greater than 9°F (5°C) may simulate an unrealistically early timing of reaching a given global warming level (GWL). Despite their unrealistic timings, these models may still be used to estimate the climate impacts occurring at a given GWL.[25]

Key Message 3.3

New Data and Analysis Methods Have Advanced Climate Science

A number of scientific developments have enabled deeper understanding of climate processes and their responses to human influence. Observational records have lengthened, and new observing systems have come online. New scenarios of socioeconomic development, and their associated emissions and land-use changes, drive updated climate projections from Earth system models. Large ensemble simulations from multiple models have enabled scientists to better distinguish anthropogenic climate change from natural climate variability. More targeted model evaluation techniques are using observations to narrow the estimated range of future climatic changes. Finally, advances in methods for extreme event attribution enabled scientists to estimate the contributions of human influence to some types of individual extreme events in near-real-time.

Advances in Earth System Observations

Surface and satellite observational products continue to provide deep insights into recent changes in the Earth system. New analyses based on long-term surface observations provide improved constraints on regional plant productivity and the moderating influences of water and nutrients (e.g., AmeriFlux sites and National Ecological Observatory Network [NEON] domains), on surface and subsurface runoff (e.g., USGS observing networks), on surface energy balance (e.g., Atmospheric Radiation Measurement [ARM] and other Baseline Surface Radiation Network [BSRN] sites), on uncertainty in near-surface temperatures (e.g., Goddard Institute for Space Studies Surface Temperature [GISTEMP]), and on atmospheric CO_2 and related gases (e.g., NOAA Earth System Research Laboratories Global Monitoring Laboratory [NOAA ESRL GML]). In situ measurements of ocean temperature, salinity, and key biogeochemical concentrations are provided by buoys, ship tracks, floats and drifters (NOAA Global Drifter Program [GDP]), and Saildrones. Extended records from the Clouds and the Earth's Radiant Energy System (CERES) and Atmospheric Infrared Sounder (AIRS) satellite missions now provide increasing confidence in warming of the Earth's atmosphere and surface. Continued analysis of the now 30-year record of sea level heights from a series of satellite altimeters provides observations of a recent acceleration in sea level rise. However, continuing declines in the number of active in situ precipitation monitoring stations threaten to produce gaps in our precipitation observation record.[26]

Recently deployed observing systems promise a deeper understanding of Earth's physical systems and reduced uncertainty in climate projections. Recent NASA missions include the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) thermal imager, focused on vegetation temperature and response to climate stressors; the Global Ecosystem Dynamics Investigation (GEDI) ecosystem lidar, focused on the forest canopy; the Earth Surface Mineral Dust Source Investigation (EMIT) spectrometer; and the Surface Water and Ocean Topography (SWOT) mission in conjunction with the Centre National d'Études Spatiales, the Canadian Space Agency, and the United Kingdom Space Agency, focused on measuring surface water on land and ocean sea surface height. Other recently launched or forthcoming missions include NASA's Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) and NOAA's Joint Polar Satellite System-2 (JPSS-2), focused on tropical cyclones and other extreme weather events. Additional frontiers in satellite-based climate monitoring include both hydrological (e.g., snow thickness) and atmospheric (e.g., clouds and atmospheric composition) properties. Besides satellite observations, NASA Jet Propulsion Laboratory's Airborne Snow Observatory (ASO) and its commercial successor have performed numerous snow surveys, enabling extremely detailed

maps of mountain snowpack. Also, recent efforts by USGS on the Next Generation Water Observing System (NGWOS) are enhancing the quality of real-time data on water quantity and quality from fixed and mobile instruments.

Combined with newer algorithms and data assimilation techniques, a growing number of observational data products enable tighter constraints for modern reanalysis datasets, such as Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2) and the European Centre for Medium-Range Weather Forecasts Reanalysis, Version 5 (ERA5). Improvements in the number and quality of observational data products have also enabled new process-oriented metrics and diagnostics (e.g., Leung et al. 2022;[27] Maloney et al. 2019;[28] Simpson et al. 2020[29]), which in turn enhance the validation of Earth system models (ESMs).

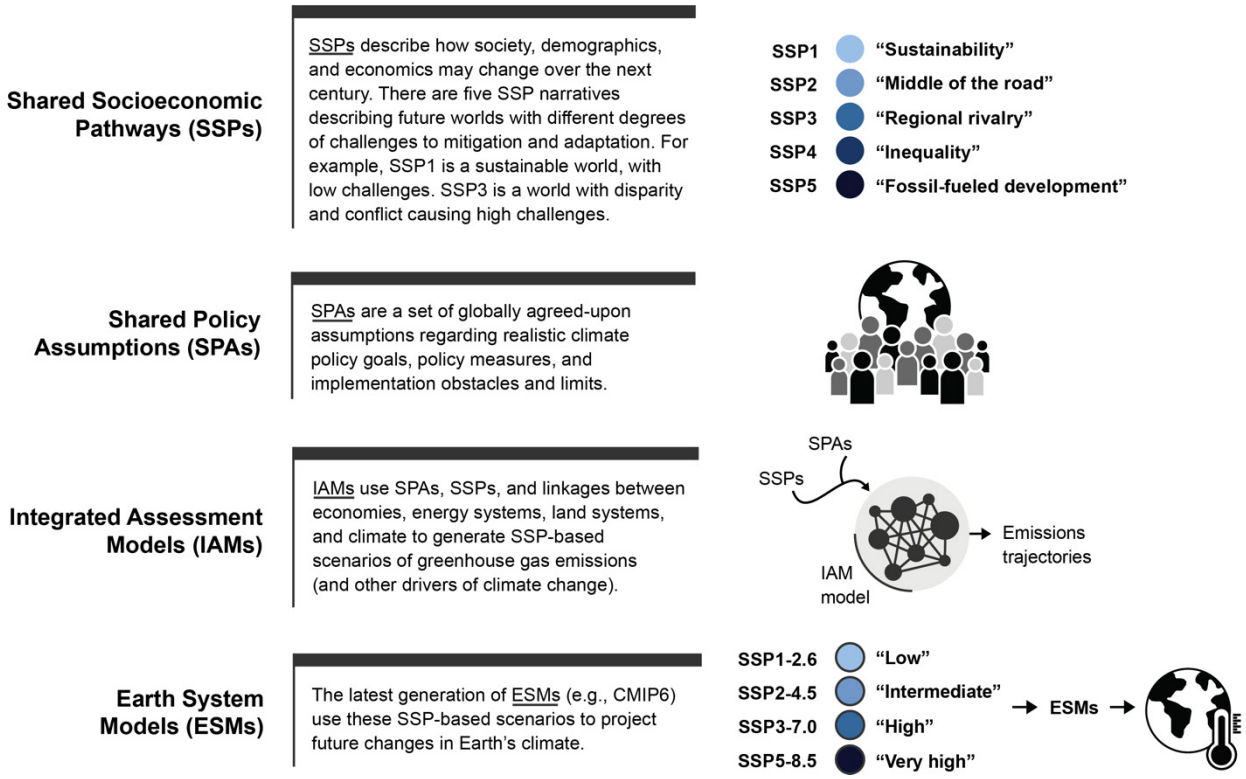
New Scenarios and Climate Projections

A new generation of ESMs has produced an updated set of projections under many new policy-relevant scenarios. A number of ESMs have been run at significantly higher resolution (about 20–50 km) than the previous standard (about 100–200 km) for focused experiments to explore particular aspects of climatic changes, like tropical cyclones, that cannot be simulated by coarser-resolution models.

The Scenario Model Intercomparison Project (ScenarioMIP)[30] organized the main set of 21st-century projection experiments under the latest phase of the Coupled Model Intercomparison Project, CMIP6. These CMIP6 projections used newly developed scenarios based on Shared Socioeconomic Pathways (SSPs; Figure 3.4).[31,32,33] Five SSPs represent alternative plausible trajectories of 21st-century GDP and population growth and the pace and pervasiveness of socioeconomic and technological progress within individual nations and across the world (see Table 3 in the Guide to the Report). SSP-specific drivers are used in integrated assessment models (IAMs) to simulate the corresponding evolution of the energy system and the resulting greenhouse gas trajectories. These are in turn used by ESMs to drive their 21st-century projections. Some of these trajectories are also modified by imposing mitigation policies that meet specific warming targets (e.g., 1.5°C [2.7°F] or 2°C [3.6°F] above preindustrial levels) by the end of the century.[34] Figure 3.4 describes this process step-by-step.

Note that the mitigation assumptions in the various scenarios are not directly relatable to the mitigation discussion in Chapter 32, where the analysis is specifically centered on the current mitigation targets of the US in view of the Paris goals. The stringent goals of net-zero CO_2 emissions by 2050 that Chapter 32 discusses for the US are, however, consistent with the lowest scenario adopted in ScenarioMIP.

SSP-Based Scenarios and Their Use in Climate Model Projections



Projections of future climate involve a multistep process using scenarios about future socioeconomic developments, policy goals, and emissions to drive Earth system models.

Figure 3.4. The graphic shows the chain of development leading to Earth system model experiments under CMIP6 ScenarioMIP, the most up-to-date 21st-century climate change projections. Five societal development pathways (the SSPs) were produced. Then, assumptions about climate mitigation policies that could be consistently applied to those socioeconomic futures were developed (the SPAs). Integrated assessment models took these baseline or mitigated pathways and produced alternative plausible trajectories of greenhouse gas emissions and land-use change. Earth system models used those emissions and land-use changes as inputs to produce the new CMIP6 scenarios of climate outcomes. Figure credit: Pacific Northwest National Laboratory, NOAA NCEI, and CISESS NC.

The new scenarios are labeled "SSPX-Y," where SSPX (with X ranging from 1 to 5) identifies the SSP used to produce the greenhouse gas trajectories and Y indicates the magnitude of the radiative forcing by 2100 in W/m^2. The main 21st-century trajectories from the CMIP6 ensemble are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, along with SSP1-1.9, the lowest emissions trajectory, which is designed to stay below 1.5°C (2.7°F) of warming above preindustrial levels. These scenarios are intended to provide a representative set of plausible alternative pathways of greenhouse gas and aerosol emissions and land-use changes, according to alternative societal and economic development trends over the 21st century. Three new scenarios correspond to three of the Representative Concentration Pathway (RCP) scenarios used in CMIP5 in their overall forcing levels (SSP1-2.6 with RCP2.6, SSP2-4.5 with RCP4.5, and SSP5-8.5 with RCP8.5), albeit with different details in their composition of gases and land use. Scenario projections can be used to explore climate outcomes under a coherent future trajectory of greenhouse gases and other anthropogenic forcings.

An alternative perspective on the effects of climate change uses GWLs as an organizing principle. One can ask when a certain GWL will be reached for a given scenario and climate model, thus connecting the two perspectives. CMIP6 includes many experiments performed by many ESMs at about 100 km resolution.[35] A multimodel approach, the High Resolution Model Intercomparison Project (HighResMIP),[36] is featured for the first time in CMIP6 to systematically investigate the impact of horizontal resolution. Models par-

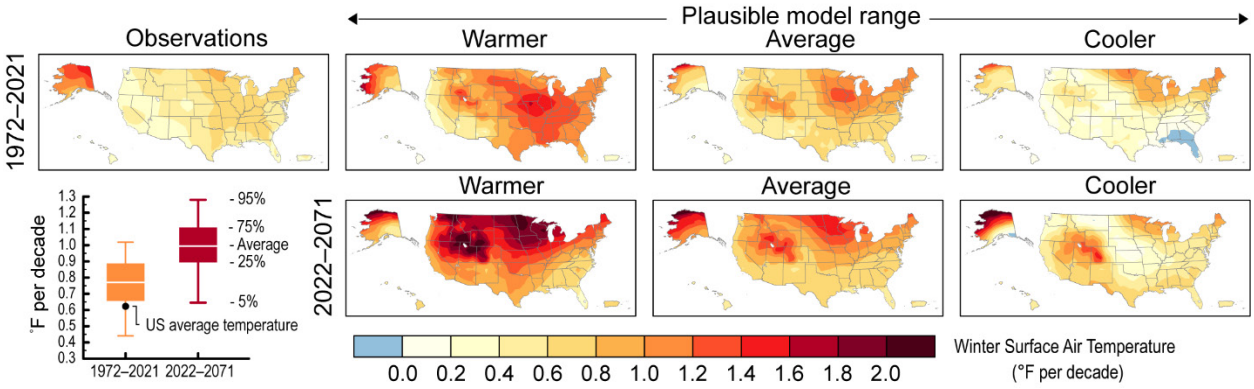
ticipating in HighResMIP have resolutions between 20 and 50 km and show more realistic simulations of intense storms and resulting precipitation.[37,38] At these resolutions, they can explicitly represent tropical cyclones,[39,40,41] and their simulations support the conclusion of a global decrease in tropical cyclone frequency[42] together with an increase in intensity with warming. Their more refined topography also enhances their representation of local processes, such as the effects of warming on mountain snowpack—an important water source for the western United States.[43]

Storyline simulations are another strategy to develop future projections.[44,45,46] In one variation of this approach, ensembles of short initialized weather hindcast simulations under imposed warming conditions can provide actionable information at regional or local scales.[47,48,49] Longer multiyear simulations can also be performed to understand changes in the statistics of weather extremes and storm characteristics (e.g., Chen et al. 2023;[50] Gutmann et al. 2018[51]) or to explore future change in climatic extremes such as drought (e.g., Ullrich et al. 2018[52]).

Large Ensemble Simulations

Many realizations of the past and future climate are generated from climate model simulations started from initial conditions that are slightly perturbed from one another. These small random perturbations, the so-called butterfly effect, can subsequently alter the chaotic sequence of weather and climate events and, hence, the future course of the variability simulated by the model. Recently, climate model experiments have been conducted using multiple climate models with small random perturbations at the start of the simulations. The advent of these initial-condition large ensembles (henceforth referred to as large ensembles) in climate modeling provides an explicit framework for quantifying the relative contributions of external drivers and natural variability to regional climate change by sampling different possible sequences of natural variability that share a common forced response.[53] The application of large ensembles to assess the possible range of climate trends at local and regional scales is a major advance in recent years (Figure 3.5). New experiments from multiple climate models that capture uncertainty due to natural variability, changes in variability, and model uncertainty have improved our ability to understand and quantify expected climatic changes and the relative contributions of human-caused climate change and natural climate variability at regional scales. A new insight from the large ensemble archive is that different models have different representations of natural climate variability and how such variability responds to anthropogenic climate change. For some variables, such as precipitation, variability consistently increases with global warming, and large ensembles provide important context for quantifying and understanding these changes.

Winter Surface Air Temperature Trends in Large Ensemble Simulations



Large ensemble simulations provide a plausible range of trends in winter surface air temperature combining the human-caused climate change and natural variability. The observed trend falls within the range simulated by the large ensemble for the historical period.

Figure 3.5. This figure shows past and projected future trends (in °F per decade) in winter (December–February) average air temperature over the United States and its territories (except the US-Affiliated Pacific Islands [USAPI]). The top row shows the observed trends during 1972–2021 (panel labeled "Observations") and the plausible model range of trends simulated by the CESM2 100-member Large Ensemble during 1972–2021 (panels labeled "Warmer," "Average," and "Cooler"). Here, "warmer" means the ensemble member with the 5th largest US-average trend, "cooler" means the ensemble member with the 5th smallest US-average trend, and "average" means the average trend across all 100 ensemble members. Note that the model range results from the combined influences of simulated natural variability and human-caused climate change. The bottom row of maps shows the plausible model range of trends simulated by the Community Earth System Model 2 (CESM2) 100-member Large Ensemble projected for 2022–2071 under the SSP3-7.0 radiative forcing scenario (panels labeled "Warmer," "Average," and "Cooler"; see above for definitions). White areas on the maps are major lakes, including Great Salt Lake, Lake Okeechobee, and Lake Tahoe. Trend values in the USAPI (not shown) are very similar to those for the Hawaiian Islands. The box plot at the lower left shows the distribution of US-average trends simulated by the CESM2 100-member Large Ensemble for the period 1972–2021 (orange) and projected for the period 2022–2071 (red). The thin white line within each box denotes the average value, and the boundaries of the box show the 25th–75th percentile range. The black dot shows the observed US-average trend during 1972–2021, which lies within the plausible model range of trends. Figure credit: National Center for Atmospheric Research.

Emergent Constraints on Future Projections

An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as "emergent constraints."[54] The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship. Observations of the current climate are used to quantify the difference between simulated and observed values in a model simulation (referred to as model bias) and subsequently constrain the future climate parameters. Research on emergent constraints has targeted a wide variety of geophysical processes.[55] For example, projections of western US runoff in CMIP5 models can be constrained by the observed sensitivity of runoff to precipitation in the historical climate.[56] A linear relationship between the projected summer warming and the model warm bias over the central US in CMIP5 models can be used to correct the future temperature projections,[57] and the observed interhemispheric asymmetry of the intertropical convergence zone has been used to correct future projections of California winter precipitation.[58]

Extreme Event Attribution

The science of evaluating the effects of human-caused climate change on extreme weather and climate events has advanced significantly. Human influence has changed the frequency and intensity of some types of extreme events, and it is now possible to quantify the influence of anthropogenic climate change on certain types of specific extreme events.

Extreme event attribution quantifies the current human influence on observed severe weather events, primarily through changes in magnitude and frequency.[59] Recent methodological advances have widened the classes of weather events analyzed and extended these analyses beyond single events to include hazards throughout an entire season (e.g., Herring et al. 2022,[60] 2019,[61] 2018;[62] Reed et al. 2022;[63] Wehner et al. 2019[64]). Confidence in attribution statements is increased when multiple methods, observations, and models lead to similar conclusions[65] and similar underlying trends are detected.[66]

Recent methodological advances include graphical methods to identify cause and effect pathways,[67] using physical insight to inform statistical models,[68,69] factual and counterfactual simulations,[70] and large ensembles.[71] The CMIP5/6 databases are often used in event attribution studies, but the relative coarseness of the model grids (100 km or more) limits applicability to large-scale events such as certain heatwaves[72] and winter storms.[73] Finer-scale events such as intense storms are often amenable to storyline hindcast simulations (see New Scenarios and Climate Projections above), using higher-resolution regional models to compare the "storm that was" with observed climate change to the "storm that might have been" without the human changes to the climate system.[74,75] However, by construction, such storyline analyses inform attribution statements about changes in the magnitude of an event not the frequency.

Attribution methods have advanced such that rapid statements can be made just weeks after an event[76,77] and even forecasted,[78] and these analyses could be made operational.[79] Despite recent progress, the human influence on some extreme weather events may not be attributable because of model limitations.[80,81]

Extreme event attribution has shown that some extreme events are happening with greater frequency, magnitude, and duration due to anthropogenic climate change. For example, climate change *very likely* made a 2016 extreme precipitation event in Louisiana heavier[77] and increased both precipitation[82,83,84] and flooding[85] during Hurricane Harvey. While these studies reveal how climate change affects extreme events, they also reveal that historical observations of climate are often insufficient for characterizing future risks.

Key Message 3.4

Humans Are Changing Earth System Processes

Human activities cause changes throughout the Earth system, including the land surface, cryosphere, ocean and atmosphere, and carbon and water cycles. The magnitude, and for some processes the direction, of these changes can vary across regions, including within the US. These changes also occur against a background of substantial natural climate variability.

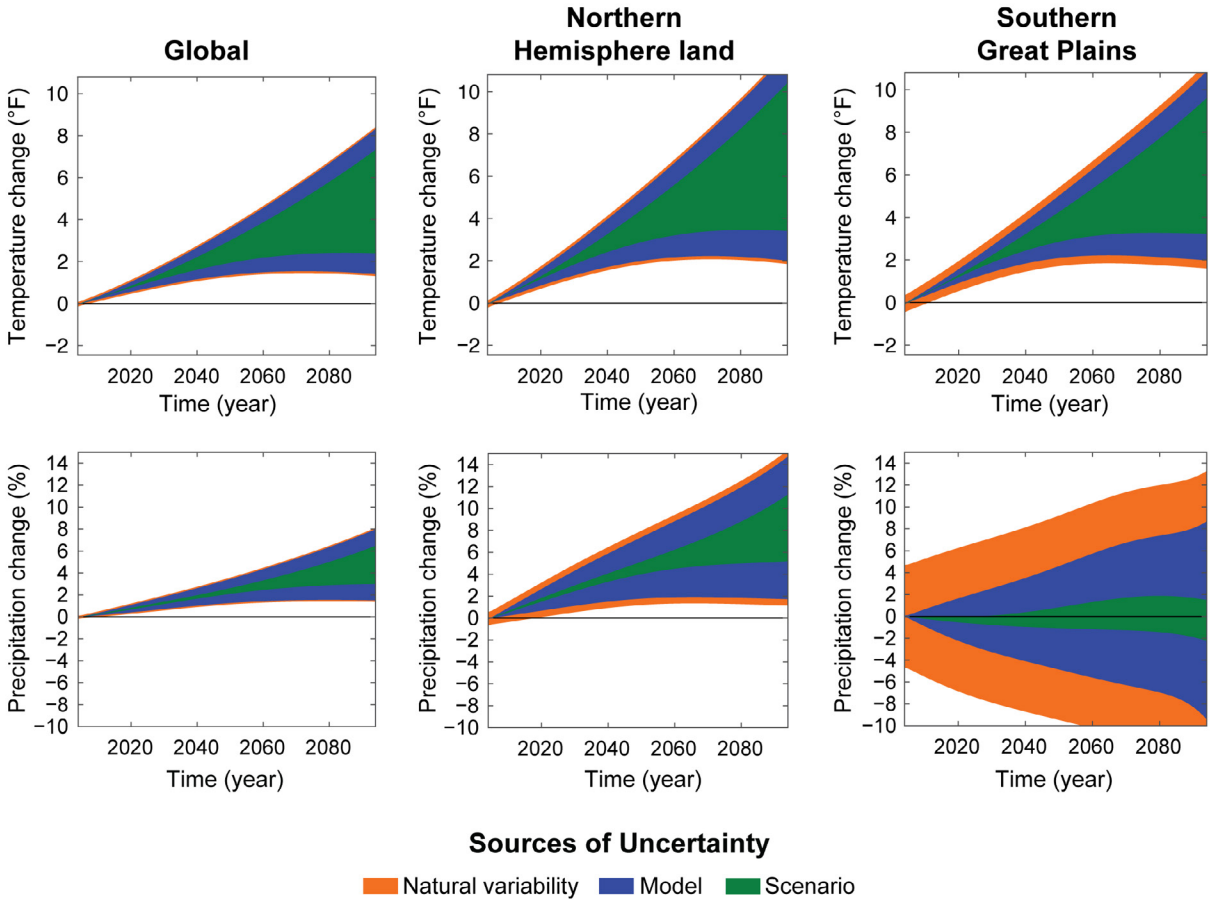
Natural Variability

At all spatial scales, the climate response is forced by anthropogenic drivers, which are *external* to the climate system. This response occurs against a background of *natural* climate variability (i.e., *internal* to the climate system). Such variability is generated by natural processes, for example, by atmosphere–ocean interaction (e.g., El Niño and La Niña events), atmosphere–land interaction, or chaotic variability within the atmosphere itself. Depending on the sequencing and magnitude of natural variability and the magnitude

of the climate change response, natural variability can mask the climate change signal, amplify it, or be overwhelmed by it. Natural variability therefore adds uncertainty to climate change projections. Because the sequencing of natural variability is largely unpredictable, this component of uncertainty in climate change projections is irreducible. This is in contrast with the uncertainty associated with the climate change response, which arises from lack of information about future greenhouse gas and aerosol emissions, as well as incomplete understanding of climate processes and associated limitations in terms of how well models reproduced observed changes. These are knowledge gaps that can, in principle, be filled (KM 3.2).

The magnitude of natural variability generally increases as spatial scales decrease (Figure 3.6). At the scale of a typical Earth system model (ESM) grid cell, natural variability is the dominant source of uncertainty in precipitation and temperature projections over much of the US. On continental scales, model and scenario uncertainties become more important.[86] Therefore, at the regional scales and the multidecadal time horizons relevant for adaptation planning, uncertainty due to natural variability can be a larger contributor to overall uncertainty in climate change than model or scenario uncertainties (Figure 3.6; e.g., Dong et al. 2021[87]). Furthermore, it is important to note that anthropogenic forcing also changes the variability of some Earth system processes, and these forced changes contribute to changes in the frequency, duration, and intensity of extreme events, such as heatwaves and heavy precipitation.

Natural Variability and Climate Model and Scenario Uncertainties



The sources of uncertainty in climate projections vary depending on timescale and geographical scale and for different aspects of the climate system.

Figure 3.6. These charts show the relative importance of different sources of uncertainty (natural variability, model uncertainty, and scenario uncertainty) for projections of moving decadal average temperature (**top row**) and precipitation (**bottom row**) for the globe (**first column**), Northern Hemisphere land (**second column**), and the Southern Great Plains (**third column**) from 1999 to 2099 (decadal averages are plotted mid-decade; for example, the x-axis starts in 2004) relative to the reference period of 1995–2014, based on CMIP6 models. Model uncertainty is calculated as the variance across models' forced response estimates. Scenario uncertainty is calculated as the variance across multimodel averages for different scenarios. The shadings are constructed as a symmetric 90% range around the multimodel, multiscenario average projection. Figure credit: Cornell University, National Center for Atmospheric Research, and Pacific Northwest National Laboratory.

Atmospheric Circulation Changes

Past and future climate changes in the United States are strongly modulated by atmospheric circulation features such as the semipermanent North Pacific and North Atlantic subtropical high–pressure systems, the Aleutian Low, the meandering jet stream stretching from the North Pacific to the North Atlantic, extratropical storm tracks and fronts, and the North American Monsoon. These regional- to continental-scale circulation features are in turn modulated by even-larger-scale overturning circulations such as the Hadley cell (see Perlwitz et al. 2017[88]). Regional circulation features over North America are also modulated by recurring remote patterns of variability such as the El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation and by variability due to the chaotic dynamics within the atmosphere (the so-called butterfly effect).

Anthropogenic forcing alters the vertical and horizontal energy and moisture distributions in the atmosphere. Atmospheric circulation is directly impacted by the resulting changes in the temperature gradient from the equator toward the poles (both in the lower and upper troposphere), the decrease in the rate that temperature falls with height above the surface, and increased latent heating.

A synthesis of observational and modeling studies estimates that the tropics have widened by about 0.5° of latitude per decade since 1979. Although climate models driven by external forcing simulate, on average, a larger expansion rate than observed, the observed rate is within the bounds of the model simulations.[89] The discrepancy between the observed and simulated rates of tropical widening is partly due to patterns of natural variability such as ENSO and the Pacific Decadal Oscillation, as well as natural atmospheric variability.[90,91]

Consistent with the tropical expansion, climate models project poleward shifts of the jet streams and storm tracks and poleward expansion of the subtropical dry zones with warming,[88] with associated impacts on the US. However, the Northern Hemisphere jet shifts are regionally and seasonally dependent (e.g., Oudar et al. 2020;[92] Zhou et al. 2022[93]). Simulations show a poleward jet shift in the central North Pacific with warming, along with an eastward jet extension that steers more Pacific storms toward California.[94,95] However, large uncertainty remains because the jet extension is also influenced by natural variability.[87] With global warming shifting the North American westerly jet poleward throughout the warm season, climate models project late-spring wetting and late-summer drying in the Midwest.[96] Poleward expansion of the North Atlantic subtropical high may intensify and extend the Great Plains low-level jet poleward, affecting warm-season precipitation in the Midwest.[97]

Besides changes connected to the tropical expansion, climate models project a weakening of the North American Monsoon with warming due to increased atmospheric stability.[98] Similar to other monsoon systems, the onset of North American Monsoon rainfall is projected to be delayed by warming.[99,100,101] In the North Pacific, warming is projected to reduce the frequency of atmospheric blocking during winter.[102]

Water Cycle Changes

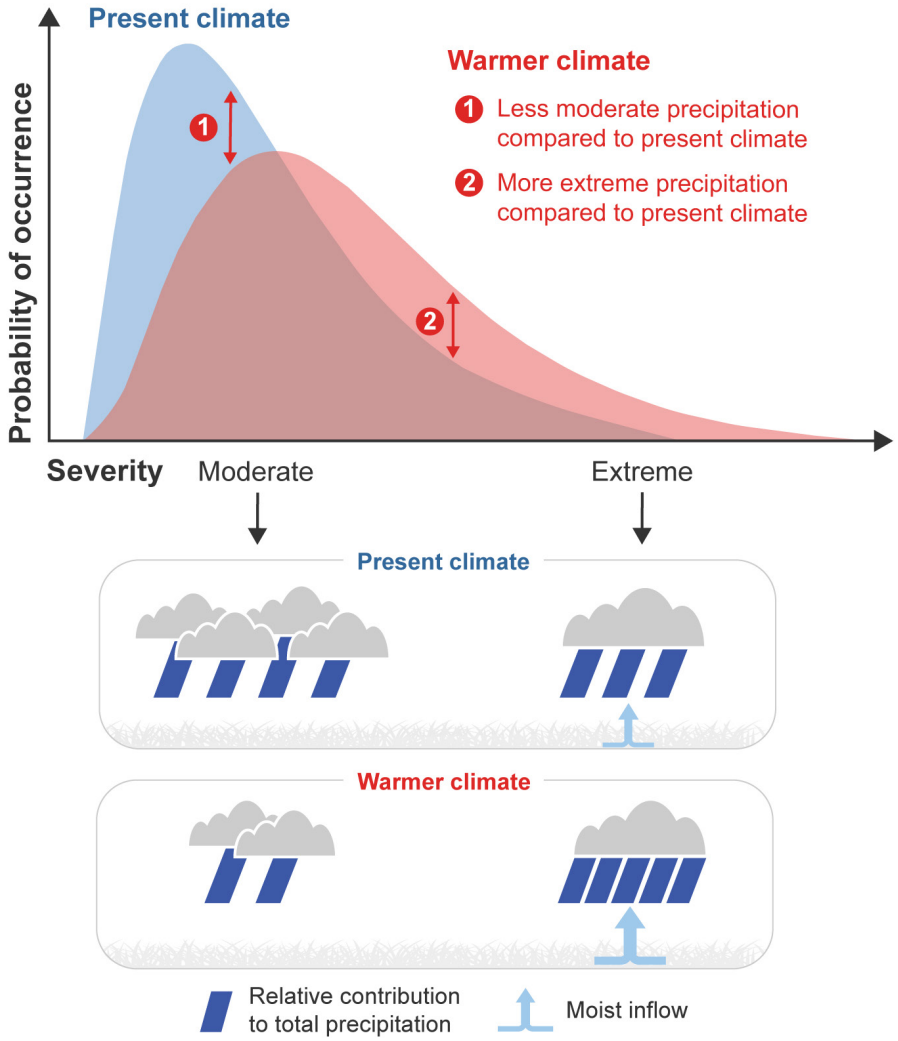
Many processes relevant to the water cycle have already begun to change and are projected to continue changing as the planet warms. These include the atmospheric circulation changes noted above as well as changes in atmospheric moisture, patterns of natural variability, the magnitude of variability of the water cycle, and the modulating role of vegetation on evaporation. These changes are driving changes in the intensity of precipitation in extreme events; snowfall, snowpack, and snow melt; and the seasonality of average precipitation and evaporation.

Seasonal and annual average precipitation and evaporation patterns have been changing with global warming. Precipitation from extreme events is projected to increase with warming (e.g., Neelin et al. 2017[103]). Heavy precipitation events constitute a large fraction of total precipitation and also a large fraction of the change in precipitation in both observations and projections.[104,105,106,107] However, it is possible to have increases in extreme precipitation but decreases in annual average precipitation at the same location due to large declines in non-extreme precipitation (Figure 3.7)[98,108,109] and overall changes in the variability of precipitation. Precipitation variability generally is projected to increase at all timescales and in most locations in response to anthropogenic forcing.[110] This implies increases in both heavy precipitation extremes and drought,[111] a phenomenon called whiplash.[112]

Water vapor factors into the intensity of precipitation extremes, such that increased water vapor due to warmer air temperatures alone would drive relatively uniform projected increases in precipitation extremes over much of the planet. Additionally, changes in circulation modulate the spatial pattern of extreme precipitation intensity change, increasing it in some regions and reducing it in others.[113] For extratropical cyclones

in summer, precipitation intensity increases, and more energetic convective storms are projected despite weakening circulation.[114] While understanding of these changes in extreme precipitation has improved, recent work has also highlighted the oftentimes large magnitude of natural variability in extreme precipitation (KM 3.5).

Changes in the Contributions of Moderate and Extreme Events to Total Precipitation with Warming



As the climate warms, extreme precipitation events become more intense and make up a larger fraction of total precipitation, while moderate events become less common.

Figure 3.7. The graphic depicts example changes in the precipitation distribution at many locations as projected by climate models. (**top**) In general, warming shifts the distribution toward a greater probability of large events and a reduced probability of light to moderate events, with only a modest change in the average total precipitation over a season or year. (**bottom**) Greater levels of water vapor in the atmosphere in a warmer world drive more precipitation during storms, when moist air masses converge. The increased water vapor convergence, or moist inflow, in very stormy areas also transports more water vapor out of surrounding areas, reducing any light to moderate precipitation there. The changes in total precipitation are often modest, because they reflect this tug-of-war between opposing changes in heavy and light to moderate precipitation. Changes in circulation can also affect the changes in all parts of the precipitation distribution. Certainty in projected changes differs among the underlying processes: the increase in water vapor and associated increase in extremes is very certain, while the changes in circulation are less certain. Further discussion related to top panel can be found in Fischer and Knutti (2016).[115] Figure credit: Cornell University and University of California, Los Angeles.

Changes in precipitation seasonality can occur with or without changes in average annual total precipitation. Increases in the amplitude of the precipitation seasonal cycle may be expected, as precipitation increases proportionally to its present-day seasonal cycle. However, other changes in the seasonal cycle of precipitation have also been found. Examples of these changes include a sharpening of the seasonal cycle in California,[112,116,117] a substantial increase in late-spring precipitation and a substantial decrease in late-summer precipitation in the US Midwest,[96] and a delayed onset of rainfall in many monsoon regions.[100,101]

Even if precipitation increases in some regions in the future, one concern is that evaporation will increase with warming, leaving the land surface drier (also see Ch. 4). Model projections and observational analyses for the US suggest that the net effect will be for warming to increase evaporation and surface drying in much of the country.

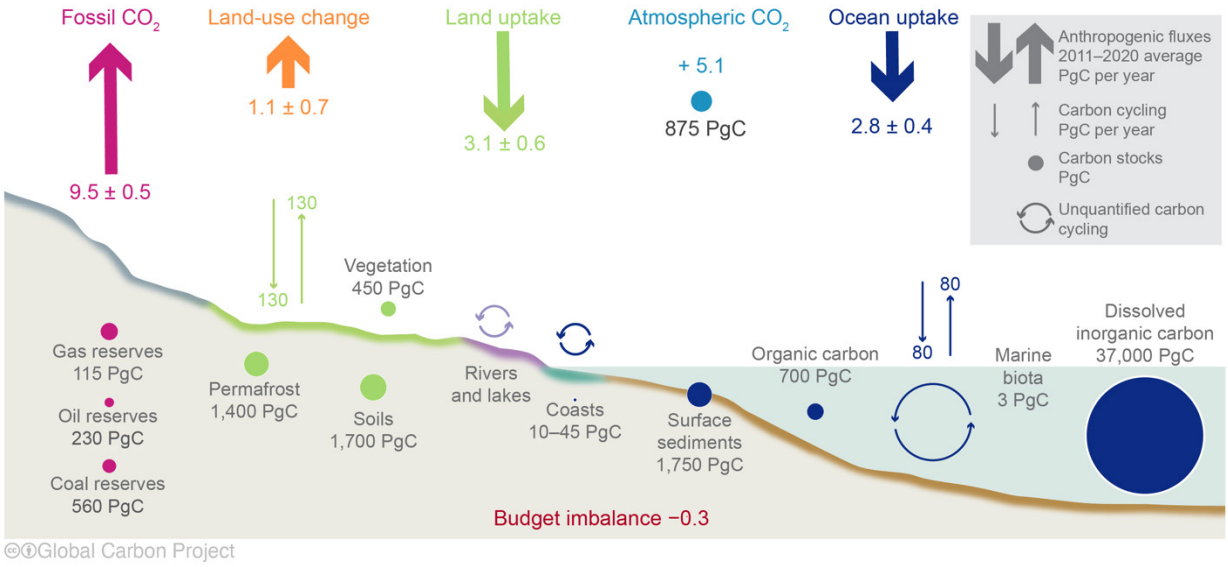
With warming temperatures, more precipitation falls as rain instead of snow. Snowpack in many mountainous regions of the US has already decreased on average over the last few decades; for example, the western US snowpack-driven reservoirs are already exhibiting changes.[118] These declines are expected to be exacerbated by greater increases in winter temperatures compared to summer temperatures in some regions due to snow albedo feedbacks. Another factor that decreases snowpack is the larger temperature increases at higher altitudes, which increase the frequency of multiyear snow droughts.[119] Decreases in warm-season streamflow have also been observed and projected because of the increase in evaporation with warmer temperatures.[120,121,122] Decreasing snowpack and increases in flooding are both concerns for water management. Increasing flooding is driven by the increasing intensity of extreme precipitation discussed above, by the shift from snowfall to rainfall, and potentially also by increases in rain-on-snow events, which can lead to rapid snowmelt (for one example, see Box 29.2).

Changes in the Carbon and Biogeochemical Cycles

Understanding of the biogeochemical responses to human-caused greenhouse gas emissions has increased due to expanded observations and improvements in models. However, uncertainty in the future evolution of the global carbon cycle remains high (KM 2.3).

Terrestrial ecosystems and the oceans take up a little more than half of the CO_2 emitted from human activities, partially offsetting the climate effects of carbon emissions. From 2011 to 2020, annual emissions averaged 10.6 ± 1.2 PgC, and the emitted carbon was ultimately distributed between the atmosphere (47%), vegetation and soils in terrestrial ecosystems (29%), and the oceans (24%; Figure 3.8).[123] Over the past six decades, the average fraction of anthropogenic CO_2 emissions that has accumulated in the atmosphere has remained nearly constant at 41%, even as fossil fuel emissions have rapidly increased.

Carbon Dioxide Sources and Sinks



While the land and ocean take up some of the carbon dioxide from human activities, the rest continues to accumulate in the atmosphere every year.

Figure 3.8. The primary sources of anthropogenic carbon are fossil fuel and land-use change emissions (upward thick arrows). While the land biosphere and ocean continue to take up the same proportion of anthropogenic carbon every decade (downward thick arrows), atmospheric carbon dioxide (CO_2) levels continue to rise as fossil fuel and land-use change emissions continue over time. Represented here is the budget of the global carbon cycle each year from estimates averaged globally for the decade 2011–2020, with flux estimates from Canadell et al. 2021.[4] Values are in Petagrams of carbon (PgC). Adapted from Friedlingstein et al. 2022[123] [CC BY 4.0].

An important question is whether the same fraction of fossil fuel emissions will continue to be offset by ocean and land biosphere uptake or whether the offset will slow or reverse over time. Answering this question depends on understanding feedbacks between the carbon cycle and climate change. The additional carbon sink on land is a consequence of multiple ecosystem processes, including increased photosynthesis responses to rising atmospheric CO_2,[124] nitrogen deposition, fire suppression, and forest regrowth after disturbances such as land clearing for agriculture.[125] Large-scale observational constraints on increased vegetation productivity due to increased atmospheric CO_2 are uncertain.[126] Ocean waters take up an increasing amount of carbon due to chemical dissolution of CO_2 in seawater, biological fixation through photosynthesis, shell formation in some organisms, and subsequent transport of carbon into deeper waters.

As atmospheric CO_2 increases, plant productivity and soil carbon also increase and are partly responsible for increases in land carbon storage, which functions as a negative feedback on climate change. However, several processes could reduce terrestrial carbon uptake, including increasing temperature and drought frequency or intensity, limitation of other necessary nutrients, and land-use changes such as deforestation. In the Arctic, potentially large biogenic releases of CO_2 and CH_4 to the atmosphere due to permafrost thaw—the timing of which may be accelerated by increasing wildfire at high latitudes[127]—could be a potentially large positive climate feedback that may alter the effectiveness of climate mitigation strategies.[128] ESMs predict a total loss of near-surface permafrost by 2100 for intermediate (RCP4.5) and very high (RCP8.5) emissions scenarios, and permafrost carbon emissions are projected to outpace increased carbon uptake from higher vegetation productivity in a warmer Arctic.[129]

Uptake of CO_2, an acid gas, by oceans leads to acidification of seawater through a series of chemical reactions that lower the pH and availability of carbonate ions in addition to other chemical changes (see

Chapter 2 for ocean acidification trend) that have been shown to be harmful to marine life.[130] Over time, uptake of carbon could slow as ocean waters become saturated with dissolved CO_2.[131] Recent observations show that ocean carbon processes are starting to change in response to the growing ocean carbon sink, and these changes are expected to contribute to future weakening of the ocean carbon sink under medium to high emissions scenarios (similar to SSP2-4.5 and SSP5-8.5 of Figure 3.7 in Jiang et al. 2019[132]).[133]

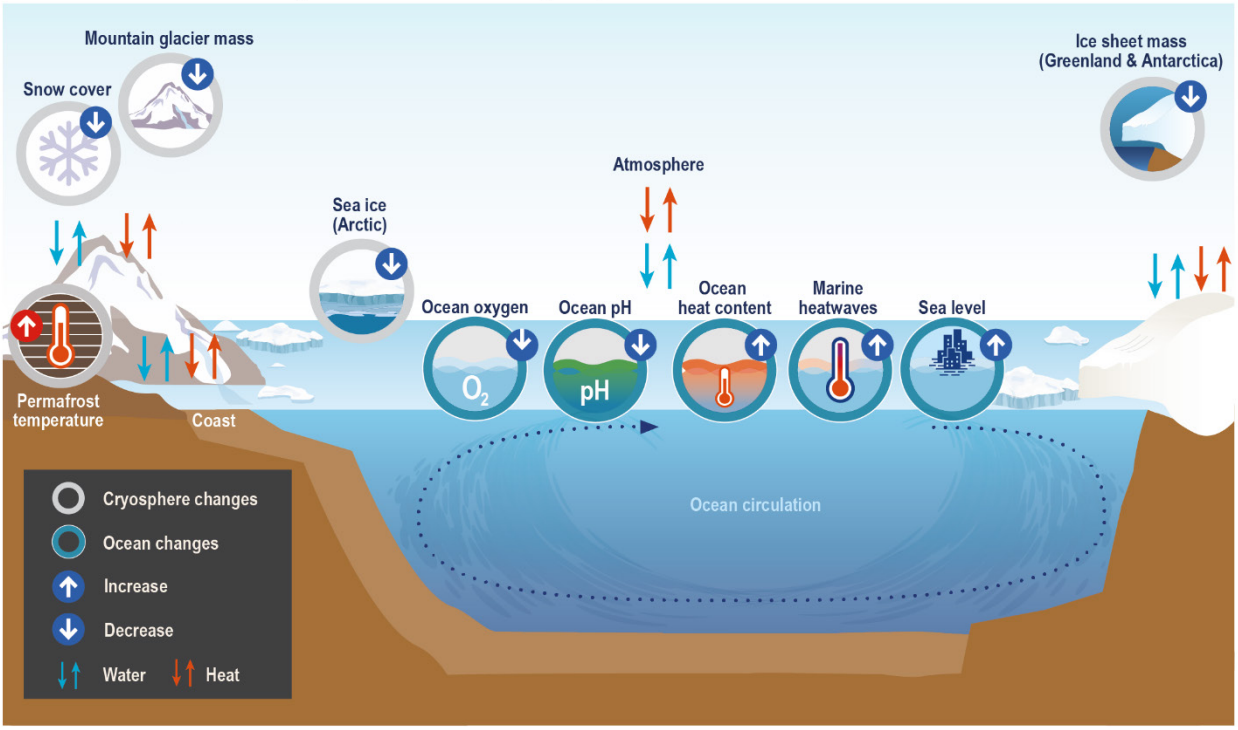
A comparison between the CMIP5 and CMIP6 generation of ESMs with respect to the representation of the CO_2 fertilization effect and carbon cycle–climate feedbacks suggests that uncertainties in these processes have remained large and virtually unchanged in recent years.[134] However, the latest generation of land models have improved representation of biogeochemical cycles,[4] and ocean models have exhibited improved representation of coupled physics and biogeochemical cycles.[135]

In the United States, the land carbon sink is dominated by forests, which have expanded in the last century due to fire exclusion in the West and to secondary forest regrowth following agricultural abandonment in the East. The growth of the North American forest biomass carbon sink is expected to become more saturated and less effective over time (Focus on Western Wildfires).[125,136] The climate change–wildfire relationship is also expected to play an increasingly dominant role in the strength of the US land carbon sink, requiring increased management of forests to meet carbon storage and other needs of society.[137] In addition, increasing temperature and moisture in some regions could lead to increased microbial emissions of CH_4 from wetlands and Arctic tundra.

Changes in the Ocean

The ocean has a large capacity to store and release heat and has been able to absorb 91% of the excess heat attributed to greenhouse gas emissions.[2] The ocean both exchanges heat with the atmosphere and moves heat from the tropics toward polar regions, where warm surface ocean waters transform into cooler, high-density waters that sink (Figure 3.9),[138] taking high carbon concentrations with them.[139] The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the global ocean circulation, transporting heat and carbon and affecting hydroclimate, hurricane activity, and coastal sea level. It is hypothesized from some proxy evidence that the AMOC has declined since the Industrial Revolution.[140] It remains uncertain whether observations support the anthropogenically forced weakening of the AMOC during the past four decades predicted by climate models.[141]

Changes in Ocean, Cryosphere, and Coastal Processes



Climate change has multiple effects on the ocean, atmosphere, and cryosphere and their complex interactions.

Figure 3.9. The figure shows important physical processes that play a role in the ocean and cryosphere, along with their linkages. Associated climate change–related effects, including sea level rise, increasing ocean heat content, ocean acidification, marine heatwaves, and ice mass loss, are also shown. The arrows indicate an exchange taking place between ice, ocean, and atmosphere. Adapted with permission from Figure TS.2 in IPCC 2019.[142]

On short timescales (annual to decadal), ocean circulation dominates the pattern of changes in ocean heat content; although on longer timescales, the spatial pattern is primarily associated with the addition of excess heat into the ocean.[143] Since 2005, Argo profiling floats have provided observations of temperature and salinity changes in the global ocean to a depth of 2,000 m. These measurements show an increase in global ocean heat content, although there is geographic variability. On shorter timescales, marine heatwaves are periods of extreme high ocean temperature relative to the long-term average seasonal cycle.[144] Persistent marine heatwaves have been observed in the northeastern Pacific since around 2014,[145,146,147] with associated negative impacts on ocean ecosystems (Ch. 27; Figure 10.2).

Changes in the Cryosphere

The cryosphere is the frozen part of the Earth system and includes ice sheets, glaciers, sea ice, permafrost, and snow (Figure 3.9). Observations of the cryosphere have expanded in recent years, including from satellites like Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) and Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2).[148] These and other complementary observations of the cryosphere show declines in ice sheet and glacier mass, snow cover, and Arctic sea ice.[149] Through efforts like the Ice Sheet Mass-Balance Inter-comparison Exercise (IMBIE),[150] there is clear evidence of loss of ice sheet mass from 1993 to 2020, and the rate of loss has increased for both the Greenland and Antarctic ice sheets. There is increased consensus regarding the behavior of many ice sheet processes. However, as the climate warms, the future response of the ice sheets and some associated processes are still uncertain.[149] Two specific processes, marine ice cliff instability[151,152] and marine ice sheet instability,[153,154,155,156,157] could lead to rapid

ice sheet loss over several decades, but the physical processes that would result in these instabilities and how they would progress once triggered remain uncertain. The decline in sea ice affects several critical functions: sea ice serves to regulate climate by reflecting solar radiation; inhibits ocean–atmosphere exchange of heat, momentum, and gases; and supports global deep-ocean circulation, polar species, and livelihoods of people in the Arctic.

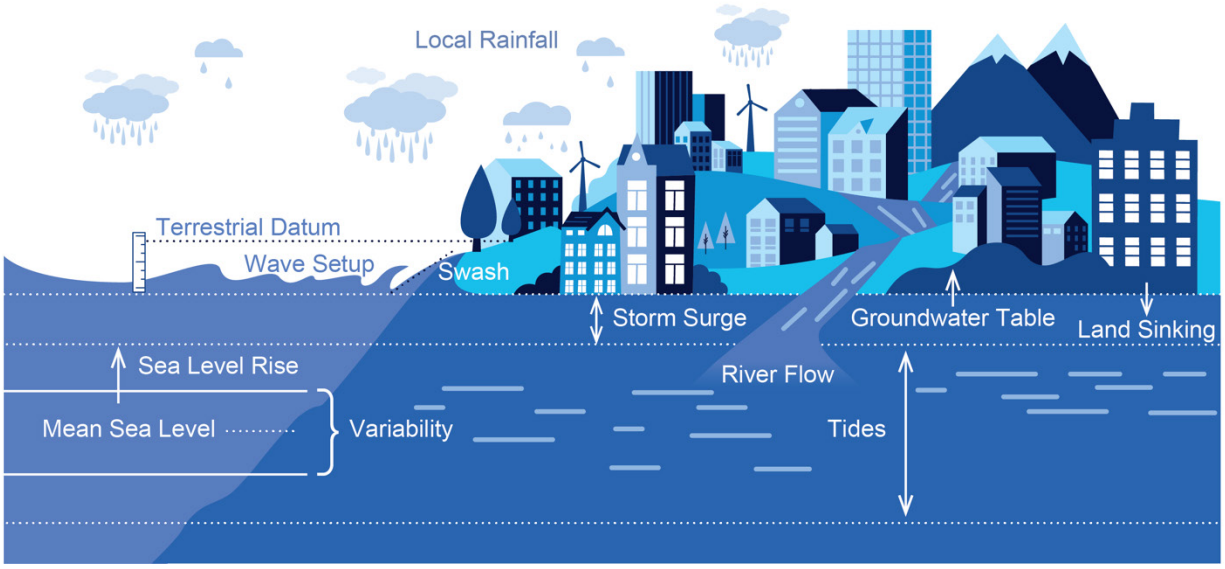
Sea Level Rise

Over long time periods, the main drivers of changes in global mean sea level (GMSL) are thermal expansion due to heating of the ocean and the addition of water associated with melting ice from ice sheets and glaciers. Human-caused changes in the movement of water between ocean and land, including from groundwater depletion and water impoundment associated with dam building, have a minor impact on GMSL, although they can increase in importance for specific time periods.[158] The increase in GMSL during the 20th century estimated from tide-gauge records has been explained by the individual processes contributing to it.[158] The rate of the 20th-century increase in sea level was faster than in any other century in at least the last 3,000 years.[159,160] In the past two decades, the changes in GMSL measured by satellite altimetry have matched the expected sea level rise based on the combination of in situ measurements of the Argo profiling floats and the observations of water-mass change from the GRACE and GRACE-FO satellites. Data from the now three-decades-long satellite altimetry record shows that the rate of GMSL rise has been increasing, driven by accelerating contributions from the underlying processes.[158,161,162]

Sea level rise is not uniform across the globe. Relative sea level rise at any specific location responds to processes that are important at regional and local scales.[149,163,164,165] On short timescales and in short records, natural variations on interannual to decadal timescales can affect estimates of rates and accelerations. Over long time periods, there are three main causes of regional variations in relative sea level: 1) sterodynamic changes (the combination of thermal expansion and ocean dynamics that is driving global sea level rise); 2) gravitational, rotational, and deformational changes that result from water moving from the cryosphere to the ocean; and 3) vertical land movement (subsidence or uplift) due to glacial isostatic adjustment, tectonics, sediment compaction, groundwater and fossil fuel withdrawals, and other non-climatic factors.[166,167]

An improved understanding of the drivers of regional mean sea level rise and how processes combine to cause sea level change at the coast has led to better assessments of the frequency, duration, and timing of high-water levels and coastal flooding events (Figure 3.10).[167] Regional sea level change has been the main driver of changes in extreme water levels.[167] Due to ongoing regional relative sea level rise and narrowing of the gap between the typical high tide and flooding threshold, the frequency of high tide flooding has increased. Natural ocean variability, including that associated with tides and large-scale climate signals that did not necessarily result in flooding in the past, is expected to lead to a rapid increase in the amount of high tide flooding in the coming decades when combined with future sea level rise (see Ch. 9).[167,168,169]

Coastal Flood Exposure



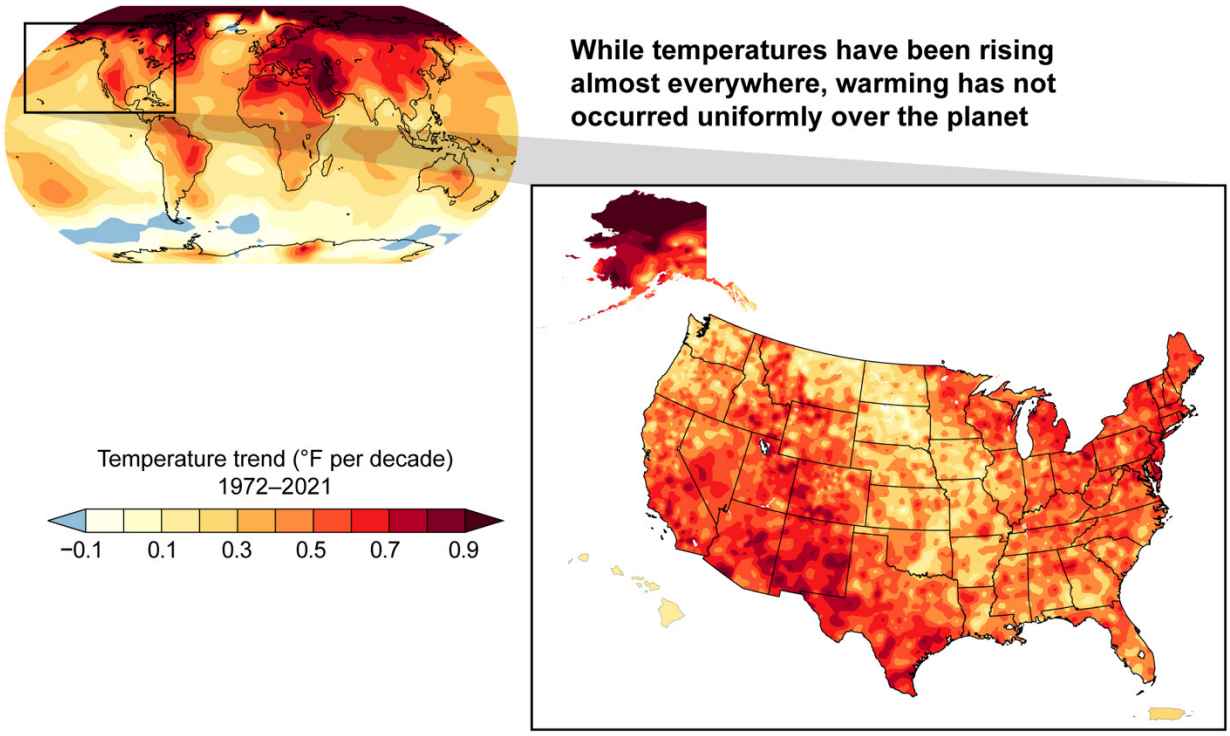
Sea level rise is increasing the probability of coastal flooding and associated impacts.

Figure 3.10. The schematic shows the physical factors affecting coastal flood exposure. Nearshore processes like storm surge, wave setup (the increase in water level due to the presence of breaking waves), and swash (wave runup and wave rundown) combine with other large-scale processes to drive impacts. Due to the clear and strong relative sea level rise signal—that is, the combination of global increases in sea level and the fact that land is sinking in many US coastal areas—the probability of flooding and impacts is increasing along most US coastlines. Source: Sweet et al. 2022.[167]

Regional-Scale Changes

Many of the changes in Earth system processes discussed above can vary across a range of spatial scales. For example, at the continental scale (less than 10,000 km), the climate system's warming response to anthropogenic forcing is affected by differences in how quickly land and ocean areas warm, with land generally warming more quickly than the ocean. This is because land areas have a lower heat capacity and thus respond more quickly than the ocean to anthropogenic forcing, and because of the larger cooling effect of evaporation from the ocean surface. Therefore, North America generally warms more than adjacent oceans (Figure 3.11). The high latitudes of the Northern Hemisphere warm the most of any region, although the reasons for this are complex and may involve processes poorly captured by global climate models.[170] Precipitation responses, arising from the changes in the atmospheric circulation and water cycle processes discussed above, tend to be organized in latitude bands such as the tropics, subtropics, midlatitudes, and high latitudes.

Regional Differences in Climate Response



While temperatures have been rising almost everywhere, warming has not occurred uniformly over the planet.

Figure 3.11. The maps show observed global (**left**) and overland US (**right**) trends (in °F per decade) in annual average near-surface temperature over the period 1972–2021. While temperatures have been increasing almost everywhere, warming has not occurred uniformly over either the planet or the US. Temperatures over land have been increasing faster than over the ocean, and the Arctic has been warming at more than twice the global average rate. Temperatures over the US have increased faster in Alaska, at high elevations, and in regions with significant seasonal snowpack. Figure credit: University of California, Los Angeles; University of California, Davis; NOAA NCEI; and CISESS NC.

At the regional scale (less than 1,000 km), variations in land surface properties are associated with differences in the local climate responses to anthropogenic forcing. Examples from the US (Figure 3.11, US panel) include greater warming at snow margins in western US mountains,[171] greater warming in inland areas separated from the coast by California mountain ranges,[172] greater warming in extremely arid landscapes,[173] shifts of precipitation downwind in mountainous areas,[174] snowfall loss at higher elevations where temperatures increase above the freezing line,[175,176] changes in snowmelt-driven runoff as a function of elevation,[177] changes in snowfall over large lakes,[178] and changes in evaporation and soil moisture due to variations in vegetation. Regional variations in the changes of temperature and precipitation are also driven partly by the regional distributions of aerosols, which interact with clouds and radiation.[179] Downscaling techniques, which convert global model outputs from lower resolution (about 100 km) to high resolution (1–10 km), are often used to simulate these phenomena for adaptation planning (see App. 3).

Key Message 3.5

Humans Are Changing Weather and Climate Extremes

Human activities are affecting climate system processes in ways that alter the intensity, frequency, and/or duration of many weather and climate extremes, including extreme heat, extreme precipitation and flooding, agricultural and hydrological drought, and wildfire (*medium* to *high confidence*).

Extreme Heat and Cold

Changes in temperature extremes in recent decades are driven primarily by trends toward warmer conditions rather than any changes in variability.[180] Consequently, the frequency and intensity of cold extremes have declined over much of the United States while the frequency and intensity of extreme heat have increased.[181] Arctic warming may also drive increases in the occurrence and persistence of circulation anomalies that are related to extreme cold and heat,[182] although the evidence that these mechanisms have played a role in recent events is mixed.[183,184] Climate change may also be contributing to "false spring" events,[185] where early warming has caused early budbreak and flowering of plants, exposing them to damaging frost and freeze events.[186]

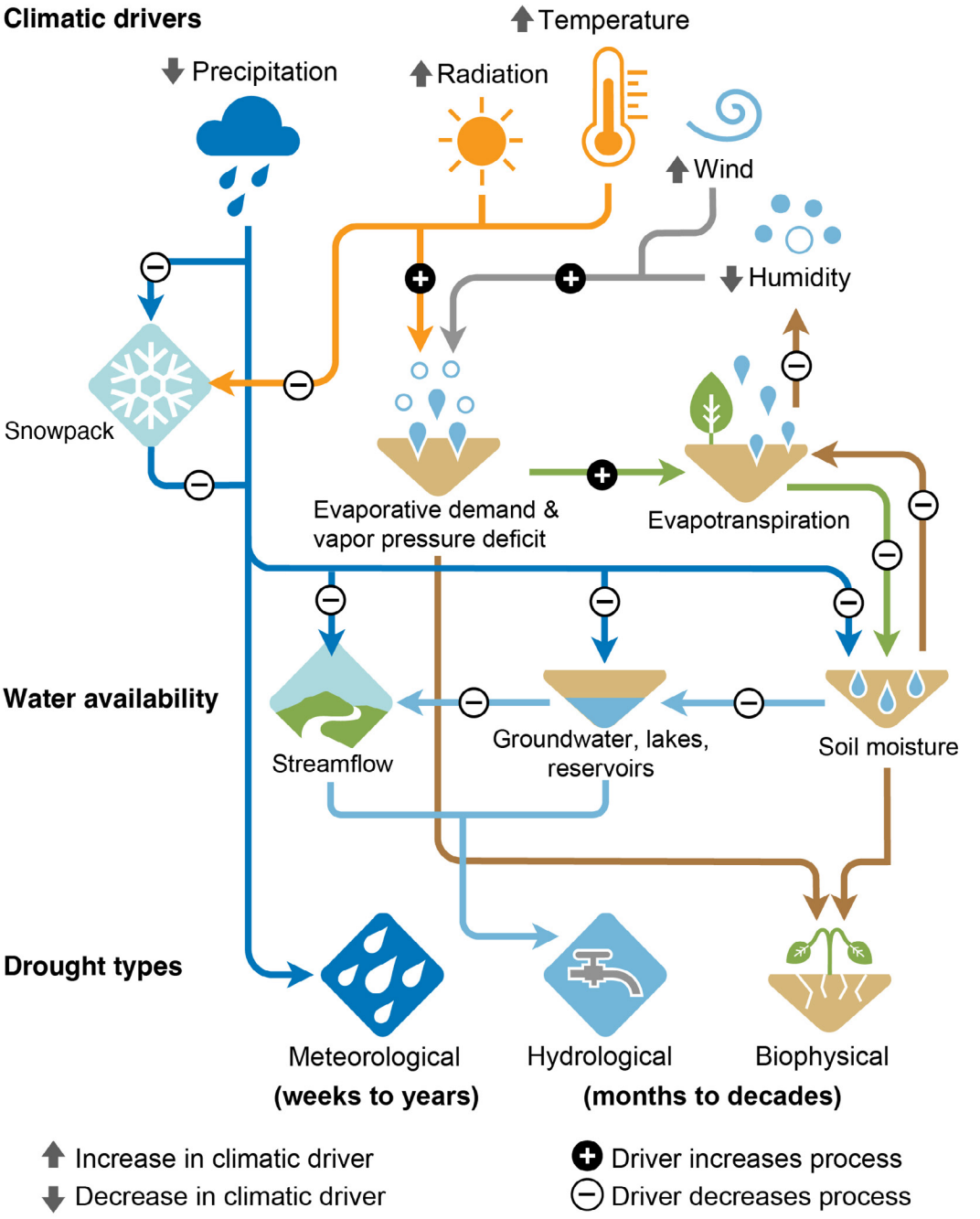
Extreme Precipitation and Flooding

Observed increases in extreme precipitation intensity at the continental scale in North America have been, for the first time, attributed to human influences.[187] With warming, it is expected, and has been documented, that more winter precipitation will fall as rain instead of snow,[188] although the projected intensity of most extreme snowstorms remains uncertain.[189] Projected increases in extreme precipitation events are larger in the winter season since warming in winter is larger, including events related to atmospheric rivers.[190] Precipitation associated with hurricanes increases with warming at least as much as water vapor,[42] and the heaviest events can increase at an even greater rate.[63,191,192] Where and when increases in extreme precipitation manifest in any given year or even decade is strongly subject to natural variability (see also KM 3.3). Notably, increases in extreme precipitation events do not always directly translate to increases in river flooding, in part because of the many processes at the land surface that affect flood events (KM 4.1; Figure 4.8).

Drought

Drought is broadly defined as a transient period of below-average water availability, typically expressed in terms of fluctuations in precipitation, soil moisture, or streamflow and runoff.[193] Drought is a complex phenomenon (Figure 3.12) that depends on fluctuations in moisture supply, direct losses of moisture to the atmosphere, and ecosystem and land surface processes.[194,195,196] Western North America experienced several decadal-scale droughts during the 20th century[197] and numerous multidecadal "megadroughts" prior to AD 1600[198] and is currently experiencing an ongoing megadrought largely unprecedented over the last 1,200 years.[199,200] See Chapter 6 for more information regarding the effect of changes in the water cycle over land.

Climatic Drivers of Drought, Effects on Water Availability, and Impacts



Climate change alters the hydrologic cycle and is expected to increase drought in some regions through various process pathways.

Figure 3.12. Changes in climatic drivers (e.g., precipitation, temperature, wind, etc.) affect different aspects of the hydrologic cycle (e.g., evapotranspiration, snowpack, streamflow, soil moisture). In turn, these hydrologic shifts translate into changes in the severity, frequency, and risk of different drought types. Plus and minus signs denote the direction of change in the driver that would cause increases in drought. For example, where precipitation declines (down arrow), all drought types will increase because this reduces snowpack, streamflow, groundwater and reservoir storage, and soil moisture. Similarly, increasing temperatures (up arrow) are also expected to increase hydrological and biophysical drought by reducing snowpack and increasing evaporative losses from streams, surface reservoirs, and soils. Adapted with permission from Figure 8.6 in Douville et al. 2021.[201]

Observed and projected hydroclimatic changes in response to external forcing are highly season- and region-dependent over the US, especially in the West.[202] Natural variability also plays a prominent role in shaping hydroclimate on annual and decadal timescales,[203] as indicated by the decrease in total area coverage of low soil moisture over the US since 1915[204] and increasing Missouri River flows,[205] a region that is expected to become drier under climate change (e.g., Cook et al. 2015[206]). Climate change is expected to amplify drought, primarily through warming-induced increases in evaporative demand and surface water losses[207,208] and declines in snowfall and water stored in winter snowpack.[43] There is strong evidence that these processes are already amplifying hydrological drought severity in California,[209,210,211] the Pacific Northwest,[212,213] the Colorado River basin,[121,214] and across southwestern North America.[200] However, there are uncertainties in how these processes may present in the future. For example, changes in plant water use in response to increasing temperatures and rising atmospheric CO_2 are complex and poorly understood and may either ameliorate[195] or amplify[215] soil moisture and runoff droughts at the surface.

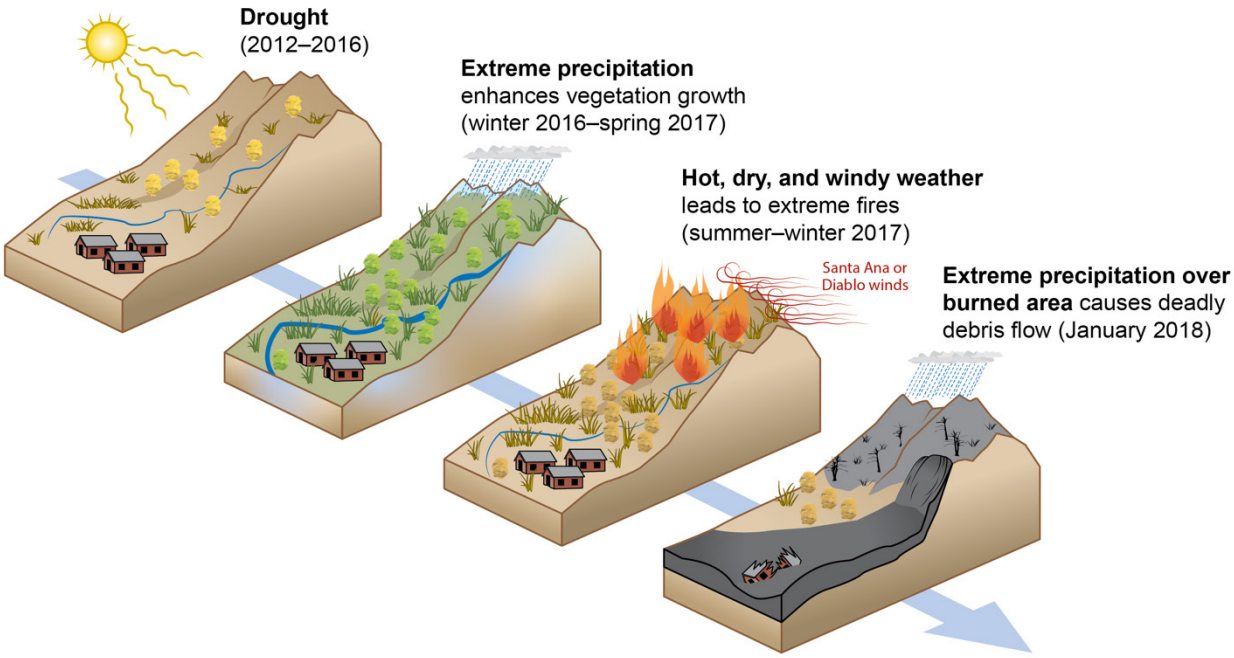
Wildfire

The direct influence of climate change on modern and future wildfire activity arises from the effect of warming on fuel moisture content and flammability (Focus on Western Wildfires). Flammability is directly related to the vapor pressure deficit (VPD), an integrative measure of atmospheric aridity or dryness. High VPD is strongly associated with the hot and dry weather conditions conducive to the intensification and spread of wildfires, as well as with drier fuels at the surface. In recent decades, warmer temperatures, declines in humidity, and increases in VPD have caused large-scale increases in fire weather[216] and areas burned by wildfire[217,218,219] across the West. From 1984 to 2015, about half of the increase in burned area across the western United States is attributable to increases in fuel flammability caused by anthropogenic climate change. These climate change–driven increases in wildfire burned area are expected to continue into the coming decades, as fuel availability is not expected to be a limiting factor before 2050.[220]

Compound Events

Compound events refer to the combination of multiple weather or climate events—which individually may not be extreme—that together pose risks to human or natural systems (see example in Figure 3.13)[221,222,223] and are described in further detail in Focus on Compound Events. Since climate change may affect the frequency and magnitude of the individual components of compound events in different ways, changes in compound events can be complex. Recent advances in statistical techniques used to describe compound events[224,225,226,227] offer rigorous ways to quantify changes. Progress has also been made in categorizing compound event types in this rapidly evolving field.[223,228,229]

Consecutive Events Leading to and Resulting from Wildfires



Consecutive events caused significant human health and economic impacts in Southern California from 2012 through 2018.

Figure 3.13. A series of events in Southern California produced a cascade of impacts on human health and the economy. These include (from top left to bottom right): a prolonged drought from 2012 to 2016; above-average winter precipitation in 2017, enhancing growth of fuels; a dry, warm spring and summer, reducing moisture levels and drying existing vegetation; record-setting Santa Ana winds; fires occurring shortly thereafter; and rainfall over the burned area, leading to debris flow event in Montecito, CA. Adapted from AghaKouchak et al. 2020;[230] modified with permission from the Annual Review of Earth and Planetary Sciences, Volume 48 © 2020 by Annual Reviews, http://www.annualreviews.org.

Traceable Accounts

Process Description

Team members were selected from two sources: 1) the pool of nominations received via the public call for authors and 2) candidates identified by the chapter lead author, federal coordinating lead author, and agency coordinating authors from their extended networks and recommendations they received. The team was selected based on a thorough review of nomination packages received, with diversity of background and experience being a primary evaluation criterion for team makeup. Considering the areas of expertise needed for the chapter, as summarized below, selections were made to ensure diverse representation across multiple axes.

- Long-lived and short-lived climate forcers and biogeochemical cycles
- Land-use and land-cover change and biogeochemical cycles
- Climate response and internal variability
- Scenario development
- Climate feedbacks and response
- High-resolution modeling
- Regional climate change
- Climate model diagnostics and metrics
- Extreme event attribution
- Cryosphere and sea level rise
- Precipitation variability and extremes
- Drought and paleoclimate
- Hydrologic and heat extremes

Given that the scoping of this chapter is related solely to physical system processes and not impacts, risks, and vulnerabilities, it was determined early on in the process, and with the consent of the Federal Steering Committee, that stakeholder engagement meetings were not required for the data-gathering process. Authors communicated primarily through email and bimonthly (twice per month) team meetings to discuss chapter progress and any issues arising during the assessment of the literature.

Key Message 3.1

Human Activities Have Caused the Observed Global Warming

Description of Evidence Base

Evidence of human drivers of global warming is provided by identifying the human-induced components that perturb Earth's energy budget and by understanding how these have evolved over long timescales. The potential for surface warming due to increases in carbon dioxide (CO_2) emitted from human activities was first identified in the 1800s,[231,232,233] and scientific understanding of the effect of anthropogenic CO_2 emissions on the climate strengthened with more than a century of advances in theoretical developments as well as through laboratory and in situ measurements.[234] The effect of other human drivers on climate, including non-CO_2 greenhouse gases (GHGs), land-use change, and aerosols, was also recognized by the 1970s. Assessment of multiple lines of evidence, including proxy records, ice core records, and direct observations,

provides unequivocal evidence of the role of human activities in increasing atmospheric levels of GHGs and aerosols over the industrial era. For the latest observational evidence of long-term changes in GHG abundances, the reader is referred to Figure TS.9 in the IPCC AR6 WGI Technical Summary,[13] which shows a strong increase in well-mixed greenhouse gases since the 19th century that is exceptional over the long term. Global average annual anthropogenic emissions of these gases reached the highest levels in human history over the present decade based on assessment of multiple lines of evidence.[4]

Human-induced emissions of GHGs alter the atmosphere's radiative balance and lead to a climate response. Earth system model simulations reproduce the observed global surface temperature trend only when human-induced climate drivers are included. Multimodel attribution experiments in support of the different phases of the Coupled Model Intercomparison Project (CMIP) have consistently shown the majority of the observed global warming to be human-induced, while that attributable to natural drivers is small.[235]

Major Uncertainties and Research Gaps

Although there is *very high confidence* in the measured increases in atmospheric GHGs since preindustrial times, attributing these increases to anthropogenic emissions or natural emissions is subject to some uncertainty (e.g., Saunois et al. 2020;[236] Tans 2009[237]). Fossil fuel emissions of CO_2 have the lowest uncertainty because of the direct relationship between combustion and emissions. Since radiocarbon ($^{14}CO_2$) is absent in fossil fuels, measurements of atmospheric $^{14}CO_2$ can be compared to CO_2 emissions inventories based on fuel consumption. Comparisons show agreements within the uncertainty bounds of the measurements.[238] However, there are discrepancies between different methods for quantifying CO_2 emissions and uptake related to land-use changes, the size of land uptake in the northern extratropics, and the strength of the ocean carbon uptake over the past decade.[123] For land-use change, a lack of historical land-cover information presents an important limitation. Likewise, inadequate coverage of datasets used to inform models of carbon exchanges between the biosphere and oceans and the atmosphere results in uncertainty for both process-based models and atmospheric inversions.

For methane (CH_4) emissions and removals, uncertainties are potentially larger than for CO_2. Emissions of CH_4 are usually the result of unintentional leakage from oil and gas infrastructure or the result of microbial processes that result from agriculture, livestock, or waste treatment. This unintentional leakage makes quantifying emissions using inventory methods difficult. However, measurements of the stable isotope of CH_4 ($^{13}CH_4$) imply that microbial sources are the primary drivers of recent atmospheric CH_4 growth, with smaller contributions from fossil fuel production. Measurements of $^{13}CH_4$ provide insight into sources, because microbes prefer to use the lighter carbon isotope (^{12}C) for metabolism, so an increase in microbial sources will mean isotopically lighter atmospheric CH_4. Although the atmospheric record of CH_4 ($^{13}CH_4$) only extends over the last two decades, measurements from ice cores suggest that prior to the recent trend toward isotopically lighter atmospheric CH_4, the trend was toward isotopically heavier CH_4, as expected due to isotopically heavier fossil fuel emissions.

Other important sources of uncertainty include difficulty in constraining atmospheric chemical destruction and uncertainty in the distribution and processes determining natural emissions. Studies comparing bottom-up estimates of emissions using inventories and emissions models with estimates from atmospheric inversions highlight uncertainties in the estimates.[236] Other studies using atmospheric observations of stable isotopes of CH_4 have suggested that global fossil fuel emissions are, in all probability, higher than those estimated by inventories.[5,239]

Description of Confidence and Likelihood

There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over

this period. Observations clearly show that concentrations of major GHGs have increased in the atmosphere since preindustrial times. Uncertainties in natural chemical removals and emissions can be significant. Sporadic changes in natural climate drivers, including solar activity and volcanic eruptions, temporarily influence surface temperatures. However, reconstructions and proxy records do not indicate any evidence of exceptional activity in these climate drivers over the past several hundred years.[10] In sum total, uncertainties in the magnitude and variability of climate drivers are not expected to change the central conclusion that anthropogenic emissions have caused the significant increases in GHGs.

Key Message 3.2

The Estimated Range of Climate Sensitivity Has Narrowed by 50%

Description of Evidence Base

The assessment of climate sensitivity and climate feedbacks follows that of Sherwood et al. (2020)[21] and Forster et al. (2021),[2] which were subject to review by peers and the community. In this Traceable Account, we provide a summary of the evidence base, major uncertainties, and a description of confidence and likelihood following these assessments. As also shown in Figure 3.3, the major change in these new assessments is to primarily base climate sensitivity estimates on observational data from multiple past periods combined with physical constraints, without directly using the values of climate sensitivity produced by climate models. Satellite observations of natural climate variability were used to provide global estimates of physical climate feedbacks,[240,241] as well as the cloud feedbacks for individual cloud types.[24,242,243,244,245] For many climate feedbacks, emergent constraints[240,246,247] support the practice of inferring long-term climate feedbacks from short-term climate feedbacks inferred from observations of present-day natural climate variability. For changes between the preindustrial period and present day, temperature analyses of in situ data provide confident estimates of global mean temperature changes.[248,249] Combining these temperature changes with estimates of effective radiative forcing for this period yields a preliminary estimate of climate sensitivity acting over the historical period. This preliminary estimate is now thought to be an underestimate of the climate sensitivity for CO_2 doubling because climate feedbacks are sensitive to the pattern of sea surface temperature warming, and the pattern of warming in the historical period differs markedly from that expected for doubling of CO_2.[173,250] Inferring climate sensitivity from paleoclimate changes relies on accurate estimates of temperature and radiative forcing changes for well-studied stable periods in the past, such as the Last Glacial Maximum (~20,000 years ago),[251] the Mid-Pliocene Warm Period (~3 million years before present),[252] and the Paleocene–Eocene Thermal Maximum (~56 million years before present).[253] To estimate a present-day climate sensitivity from paleoclimatic data, estimates of changes in temperature and radiative forcing must be derived from proxy data. It is also necessary to consider how different ice sheet and continental configurations acted as forcing,[254] as well as the temperature dependence of climate feedbacks.[255]

Synthesizing the implications for climate sensitivity from this extremely diverse body of evidence is nontrivial. Synthesis requires the development of a common framework to treat evidence based on extensions to the forcing–feedback paradigm,[2,21,256] as well as the sustained multiyear interaction of scientists from diverse research communities. Mathematical methods used in synthesis vary from complex Bayesian methods[21] to simpler consistency arguments.[2]

Major Uncertainties and Research Gaps

A major uncertainty in the estimate of climate sensitivity involves the pattern of sea surface temperature warming in the Pacific for the long-term forced response to CO_2 doubling.[21] Over the last several decades, the observed pattern of warming has featured smaller warming or even cooling in the East Pacific,

increasing the amounts of low clouds and sunlight reflected back to space and thereby reducing the warming of Earth. It is thought that this pattern in the recent past is due to natural climate variability. It is expected that over the 21st century, the warming in the East Pacific will catch up to and exceed that in the West Pacific, matching the predictions of CMIP models for CO_2-dominated warming. However, if the observed recent pattern of warming includes a component of the forced response to CO_2 that models fail to predict, then climate sensitivity values at the high end are less likely.

Other key climate sensitivity uncertainties[21] include 1) the scaling ratios between feedbacks estimated from the smaller short-term temperature variability and the larger climate change expected in the 21st century; 2) the cloud feedbacks from cloud types other than the well-studied marine low clouds; 3) the magnitude of aerosol forcing over the historical period, knowledge of which is critical for determining the component of historical warming from GHGs; 4) the abundance of dust and other aerosols in the Last Glacial Maximum; 5) the characterization by proxy records of temperature, trace gases, and other forcing agents for warm periods in the deep geological past; 6) the dependence of climate sensitivity on the background state; and 7) the accounting for Earth system effects when interpreting the consequences of the paleoclimate record for a climate sensitivity applicable to 21st-century warming.

Description of Confidence and Likelihood

The *likely* ranges of climate sensitivity are derived from the synthesis of the evidence base through the framework of the forcing–feedback paradigm.[2,21,256] Confidence is *high* in the reduced range of climate sensitivity because its observational estimates are derived from three independent lines of evidence and because the three central estimates of climate sensitivity are in general agreement. The three lines of evidence are 1) evidence from natural climate variability in the present day, 2) evidence from the changes in climate from the preindustrial period to the present day, and 3) evidence from the changes in climate from various cold and warm periods in the paleoclimate record. Additional reasons for *high confidence* include a greater understanding of how physical climate feedbacks vary with the nature of changes for different timescales and a greater ability to synthesize diverse evidence from different periods in Earth's past.

Key Message 3.3

New Data and Analysis Methods Have Advanced Climate Science

Description of Evidence Base

Advances in Earth System Observations

From temperature and precipitation observations that began in the 1800s through the earliest observations of CO_2 concentration taken on Mauna Loa from the late 1950s[257] and into the satellite era,[258] observations of the Earth system have been essential for constraining climate models and improving our understanding of the climate system. Since the last National Climate Assessment was released in 2018, several major advancements in understanding of the Earth system have arisen from observational platforms.

New observations using eddy covariance measurements from AmeriFlux and NEON and subsequent science are described in Novick et al. (2018)[259] and Chabbi and Loescher (2017),[260] respectively. A deeper understanding of the water cycle derived from subsurface and surface runoff from USGS is described in USGS (2019).[261] Improvements in estimating surface energy balance from ARM and other BSRN sites is described in Wild (2017).[262] Better constraints of uncertainty in near-surface temperatures from GISTEMP comes from Lenssen et al. (2019).[248] Understanding of atmospheric CO_2 and related gases comes from NOAA ESRL GML.[263] Understanding of ocean temperature, salinity, and key biogeochemical concentrations comes from buoys, ship tracks, floats, drifters,[264,265] and Saildrones.

Observational evidence to constrain Earth's heating rate from CERES and AIRS is described in Loeb et al. (2021)[266] and Susskind et al. (2019),[267] respectively. Improved evidence of sea level rise using satellite altimetry is documented in Li et al. (2022)[268] and Nerem et al. (2018).[162] Recently deployed NASA and NOAA satellite observing systems are documented in Fisher et al. (2020;[269] ECOSTRESS), Dubayah et al. (2020;[270] GEDI), Green et al. (2020;[271] EMIT), Zavodsky et al. (2017;[272] TROPICS), Goldberg and Zhou (2017;[273] JPSS-2), and Morrow et al. (2019;[274] SWOT). NASA JPL's ASO is described in Painter et al. (2016).[275] The USGS NGWOS system is described in Eberts et al. (2019).[276]

New Scenarios and Climate Projections

The development of the set of new scenarios used by CMIP6 by the so-called parallel process[277] started while the CMIP5 simulations based on the Representative Concentration Pathways (RCPs) were produced, analyzed, and assessed in IPCC 2013[278] (the stage-setting essay for the new scenarios development is Ebi et al. 2014[279]). The new scenarios are based on plausible future alternative pathways of socioeconomic development (the Shared Socioeconomic Pathways [SSPs]) from which consistent GHG emissions trajectories unfold, as opposed to simply consisting of idealized trajectories of future GHGs. Idealized trajectories (like a 1% annual increase in CO_2 concentrations or an instantaneous doubling of CO_2 concentrations) are useful sensitivity experiments, but they cannot be considered plausible, being decoupled from assumptions about human-caused emissions. About 40 modeling centers from all over the world participated in CMIP6 and ScenarioMIP.[280]

Large Ensemble Simulations

About a decade ago, the first initial-condition ("large") ensembles were created (e.g., Deser et al. 2012,[281] 2012[282]) with a single model, followed by other models[283] and large ensembles with up to 100 simulations.[284] Currently there are large ensembles from many other climate models,[53] and the model intercomparison protocol for the most recent generation of simulations encouraged large ensembles of 10 realizations for all models.[30]

Large ensembles are used to estimate uncertainty from natural variability separately from the model uncertainty among climate models.[86] They have revealed the dependence of some aspects of natural variability, like precipitation, on climate state.[110] Large ensembles have also enabled the isolation of the response to different climate forcings, independent of natural variability and assessment of the linearity of these responses[53] or lack thereof.[285] They have also been used to assess whether El Niño–Southern Oscillation (ENSO) events and their impacts on precipitation and temperature over North America will change in the future[286,287,288] and to assess how large-scale atmospheric circulation patterns that affect US weather and climate may be altered by the effects of climate change.[289] Emerging applications of large ensembles include addressing questions related to the timing of when human-induced climate change signals exceed the natural variability of the climate,[290] risk assessment,[291] US water resources,[292] air pollution and associated health impacts,[293,294] and ecosystem stressors[295] (see Deser et al. 2020[53] for other examples).

Emergent Constraints

Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.[240,246,247] Emergent constraints have also been applied to many other climate processes (see Hall et al. 2019[55] for a list). Williamson et al. (2021)[296] also provide a recent and comprehensive review of the emergent constraint literature and identify the various uncertainties in the physical and biogeochemical system responses that have been reduced in a credible way through the emergent constraint technique.

Extreme Event Attribution

Since the landmark study of Stott et al. (2004),[72] which concluded that the chances of the 2003 European heatwave doubled due to anthropogenic climate change, many different author teams have analyzed a wide variety of extreme weather events to identify if there was a human influence. This large body of literature has been developed using many different approaches that have been surveyed by the author team. Of particular interest are a series of special supplements published since 2011 in the *Bulletin of the American Meteorological Society*.[60,61,62,297,298,299,300,301,302,303] Chapter authors have contributed to these reports and have published event attribution studies in the general literature.

Confidence in attributing the human influence, if any, on individual extreme weather events is increased when multiple independent author teams arrive at similar conclusions using different methods, observational estimates, and models, coupled with a thorough understanding of the physical processes of change. The copious amount of precipitation experienced in the greater Houston area during Hurricane Harvey provides a case in point, where three different teams concluded that anthropogenic climate change led to large attributable increases in storm total rainfall.[82,83,84] Confidence in this attribution has been further increased by the subsequent studies of other hurricanes, leading to similar conclusions.[63,78,192,304]

Confidence in an extreme event attribution statement hinges on reliable long-term observations.[66] Fortunately, much of the contiguous US (CONUS) is well observed since 1950 by the NOAA Global Historical Climate Network weather station measurements of temperature and precipitation. In many locations, reliable records span an entire century.[305]

Attribution is an exercise in causal inference; climate change attribution studies borrow techniques from the well-established epidemiology literature. Typical Pearl causal inference experiments involve two groups, a controlled (or placebo) group and a tested group.[306] As there is only one Earth, climate change attribution experiments can be performed only with numerical models. The limitations of climate models impose important caveats on any resulting attribution statements. The CMIP database of global climate models (GCMs) has been extensively used in attribution statements.[307,308] However, it is best suited for extreme events of larger spatial scales matching that of the CMIP models (e.g., heatwaves). More customized numerical experiments at higher resolution may be required for more localized extremes such as intense storms (including hurricanes).[64] Granger causal inference has also been applied to long observational records to make attribution statements without using climate models.[67,309] While a weaker form of causal inference due to the possibility of hidden covariates in the underlying statistical models (i.e., statistical model construction may bias findings), Granger causal inference can add to our understanding of changes in extreme event frequency and magnitude.

Major Uncertainties and Research Gaps

Advances in Earth System Observations

Unfortunately, not all quantities relevant to the Earth system can be easily observed. Although recent satellite missions such as GRACE[310] have been able to use gravitational measurements to constrain subsurface moisture, much of the subsurface remains poorly understood. Ongoing work has also suggested that deep-ocean heat content may have been underestimated,[311] a consequence of insufficient measurements of the deep ocean. Further, in situ measurements are generally more available within developed countries and in more easily accessed regions, resulting in significant observational gaps in the Southern Hemisphere (e.g., Guo et al. 2009[312]) and at high elevation.[313,314]

New Scenarios and Climate Projections

Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that the highest scenario,

SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. The scenario development community is always testing the structural uncertainties of integrated assessment models and, therefore, the assumptions that produce the alternative emissions pathways. Timely updates of the baseline from which future projections are made, on the basis of current trends and observations of emissions, are necessary to maintain the plausibility of alternative pathways.

Large Ensemble Simulations

Much remains to be done to obtain decision-relevant information at the scale of impacts—regional to local—with quantified uncertainty grounded in understanding of the natural variability, forcing, and structural sources of uncertainty. Identifying the forced pattern of response on local scales and separating it from natural variability is a continuing challenge, which has immediate implications for predictability, climate model evaluation, and the potential to narrow uncertainty in climate projections. Another key challenge is the so-called signal-to-noise paradox, which implies that models underestimate atmospheric predictability due to incomplete representations of key atmospheric and oceanic processes.[315] Thus, as models improve, there may be the potential to deliver more skillful climate predictions. Stakeholder and decision-maker input on what uncertainty is tolerable for specific applications, and what this means for the size of large ensembles, is another outstanding topic. The role of natural variability for many impacts, including air quality, has yet to be fully addressed. Finally, the implications of potential changes in natural variability for decadal prediction and predictability are still open questions. For example, what is the timescale of predictability? How predictable is *x* variable on *y* timescale?

Emergent Constraints

Both Williamson et al. (2021)[296] and Hall et al. (2019)[55] identify major research gaps and uncertainties associated with the emergent constraint technique. Uncertainties include the following: 1) some proposed emergent constraints lack of out-of-sample testing in other model ensembles, 2) some proposed emergent constraints are characterized by a strong statistical relationship but lack a physical or theoretical framework to support the emergent relationship, and 3) some proposed emergent constraints lack observational data to constrain the future response, even assuming the emergent relationship is statistically robust and supported by a physical mechanism or theory. In addition, most emergent constraints have been applied to quantities of relevance to the global climate system. Going forward, it would be helpful to have more emergent constraints developed at the regional scale to reduce uncertainty in quantities of greatest relevance to the US or other regions.

Extreme Event Attribution

Confidence in extreme attribution statement depends on both our understanding of the underlying physical mechanisms of change as well as on the fitness of our statistical and climate models.[65] This, of course, varies significantly depending on the nature of the extreme weather event. Attribution statements about the human influence on severe heatwaves and cold snaps are generally considered to be most confident.[221] Confidence in attribution statements about extreme precipitation vary greatly depending on storm type. Hurricane precipitation has been among the most-studied event, and recent assessment has concluded that modeling and satellite studies, as well as physical understanding, provide strong evidence that hurricane rainfall rates increased and will continue to increase due to anthropogenic climate change.[221,316] The Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WGI) concluded that "event attribution studies and physical understanding indicate that human-induced climate change increases heavy precipitation associated with tropical cyclones (*high confidence*), but data limitations inhibit clear detection of past trends on the global scale."[20] Partly based on CMIP5 models, the World Meteorological Organization's Tropical Cyclone Expert Team[42] concluded: "For TC precipitation rates, there is at least medium-to-high confidence in an increase globally, with a median projected increase of 14%, or close to the rate of tropical water vapor increase with warming, at constant

relative humidity." However recent higher-resolution modeling studies, particularly event attribution studies, find that hurricane precipitation increases at a rate substantially higher than that of water vapor alone, implying dynamical as well as thermodynamical changes (e.g., Reed et al. 2021,[304] 2022;[63] Risser and Wehner 2017;[82] van Oldenborgh et al. 2017;[83] Wang et al. 2018[84]). A recent satellite-based study reinforces this interpretation.[316] Atmospheric rivers and extratropical cyclones have received less attention, but it is expected that similar conclusions will be drawn as more studies are performed. Mesoscale convective systems (e.g., storms producing hail, tornadoes, and ice) are not so well studied due to both modeling and observational limitations of these specific local-scale events.

Changes in extreme wind events, such as produced by hurricanes, derechos, or Santa Ana–type events, are also poorly understood due to model limitations in realistically simulating these phenomena.

Extreme weather changes attributable to local thermodynamic processes are better understood than those due to changes in large-scale meteorological patterns due to uncertainty in changes in circulation patterns. Thus, attributable changes in meteorological drought (defined by rainfall deficits) caused by changing rainfall patterns from circulation are less well understood, especially for CONUS, than are attributable changes in agricultural and ecological drought (defined by increases in soil moisture deficit caused by warmer temperatures).[196]

Some events are so extreme that our statistical and climate models may not be fit for the purpose of quantifying the human influence, even if our understanding is such that we are confident that there is one. The 2021 heatwave in the Pacific Northwest is a good example. Temperatures experienced during this very rare compound extreme event are outside of the bounds of the fitted generalized extreme value statistical distributions typically used to ascertain changes in event frequency and magnitude. Also, it is unclear whether the standard ensemble of CMIP models can produce the specific large-scale meteorological patterns responsible for these record-breaking temperatures. For these very rare events, the recent development of large ensembles of climate models can increase our confidence in quantitative attribution statements in some instances.[53]

Description of Confidence and Likelihood

The section is a description of factual results, so confidence and likelihood do not apply.

Key Message 3.4

Humans Are Changing Earth System Processes

Description of Evidence Base

Natural Variability

In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals (e.g., Deser 2020[317]). The mechanisms by which the climate system generates such large levels of natural variability are well documented and understood. Examples of such modes of variability relevant to North American climate include ENSO, the Pacific Decadal Oscillation, the Pacific North American pattern, and the northern annular mode. Many of these patterns have limited predictability beyond a timescale of about two weeks, leading to an irreducible uncertainty in the actual evolution of climate. A caveat here relates to the ENSO phenomenon, which has some seasonal to interannual predictability. We also note that modes of variability themselves can also be affected by anthropogenic forcing, and these signals may be predictable.[318] This idea of irreducible uncertainty applies to

future projections only. It is not meant to cast doubt on anthropogenic climate change that has already been detected in the observational record despite natural variability.[221,235]

Atmospheric Circulation Changes

Many aspects of atmospheric circulation changes have been studied using observations (global reanalysis) and model simulations. Important large-scale circulation features that influence US regional climate include the jet stream, storm tracks, the Aleutian low, the North Pacific and North Atlantic subtropical highs, North American Monsoon circulation, and others, which are strongly influenced by the overturning Hadley circulation in the tropics. In turn, large-scale circulation, such as the North Atlantic subtropical high, influences mesoscale circulation features, such as the Great Plains low-level jet that affects precipitation in the central and midwestern US. Hence, understanding how the Hadley circulation changes with warming is important for understanding changes in large-scale and mesoscale circulations affecting US regional climate. Staten et al. (2018)[89] and Grise et al. (2019)[90] synthesized previous studies documenting the poleward shift in the subsiding branches of the Hadley circulation since 1979. Both studies found that methodological differences in how the Hadley circulation is calculated can partly explain the discrepancy between the rate of tropical expansion derived from global reanalyses and model historical simulations found in previous studies. However, both studies also highlighted the challenge in detecting changes in the tropical expansion and attributing them to anthropogenic warming because of the large natural variability, particularly for the poleward expansion in the Northern Hemisphere that is more relevant to large-scale circulations affecting North America.

Besides the tropical expansion, many studies analyzed model simulations and projections of changes in large-scale circulations—such as the jet stream,[87,93,95,319] storm tracks,[320] extratropical cyclones,[189,321] and the North Atlantic subtropical high,[100,322]—and compared observed and model-simulated historical trends in sea level pressure.[323] Many of these studies used multimodel and large ensemble simulations to first determine if a robust signal of change is found and, if so, the mechanisms for how warming may influence the circulation features; the impacts of the circulation changes to precipitation are also often investigated. Model experiments allowing isolation of the direct radiative effect of CO_2, which is a fast process, versus the effect of sea surface temperature warming, which is a slower process, have also contributed to improving understanding of how increasing GHGs affect atmospheric circulation.

Water Cycle Changes

A sizeable and expanding literature describes past and projected future changes in processes relevant to Earth's water cycle.[201,324] Much of the literature on the water cycle separates its projected past and future changes into two components: one proportional to the change in water vapor—the "thermodynamic" response—and another that depends on atmospheric circulation and other factors—the "dynamic" response. Water vapor changes increase at roughly constant relative humidity with warming,[325] with variations over land and during different phases of the response[326] that are relevant to the US. Changes in circulation also modulate the spatial pattern of extreme precipitation intensity change, increasing it in some regions and reducing it in others,[113] which is the main driver of the variations in magnitude and sign of precipitation change seasonally and regionally. Precipitation variability generally is projected to increase at all timescales and in most locations in response to GHG-driven warming.[110] This implies increases in both heavy precipitation extremes and drought,[111] a phenomenon called whiplash.[112]

Changes in the Carbon and Biogeochemical Cycles

Observations show that about half of annually emitted CO_2 from human activities is absorbed by the terrestrial biosphere and oceans.[327] The observational record of atmospheric CO_2 growth and estimates of fossil fuel emissions based on economic fuel statistics are used to estimate the residual total uptake of carbon by the terrestrial ecosystem and the ocean. Determining the amount of uptake for land and oceans

is more complicated and uncertain. For the oceans, upscaled global measurements of the partial pressure of CO_2 (pCO_2) in seawater and total carbon in organic and inorganic compounds dissolved in interior ocean waters are used to estimate current and cumulative carbon sinks (e.g., Rödenbeck et al. 2015;[328] Takahashi et al. 2009[329]).

On land, direct measurements of atmosphere–land biosphere fluxes are used to understand carbon sources and sinks and their variability on daily to interannual timescales.[330]

Changes in Ocean, Cryosphere, and Sea Level

Over the course of the 20th century, sea level rise occurring on global scales estimated from reconstruction created from tide-gauge records has been explained by the individual processes contributing to it.[158] These process contributions were estimated from a combination of direct observations and observation-driven reconstructions. Using modern observation systems, global sea level rise from satellite altimetry between 2002 and 2017 has been explained using the in situ measurements of the Argo profiling floats and the observations of water-mass change from the GRACE and GRACE-FO satellites,[331] demonstrating closure of the global sea level budget. As seen in both tide-gauge and satellite records, the rate of global mean sea level rise has been increasing, driven by accelerating contributions from the underlying processes.[158,161,162]

At the regional level, similar studies have assessed the rates of sea level rise and performed similar budget studies as those conducted on global scales. The combination of models, reconstructions, and observations allows for accounting of all the relevant processes, and an understanding of the drivers of total sea level rise has been demonstrated on regional scales across a range of different timescales in several studies (e.g., Frederikse et al. 2017;[332] Harvey et al. 2021;[333] Rietbroek et al. 2016;[334] Walker et al. 2021[160]). The current relative sea level observation network measures the dominant processes contributing to regional sea level, and this has supported more dedicated, process-level studies on sea level rise.

Regional-Scale Changes

It has been well established since the earliest climate change assessments (e.g., IPCC 1990;[335] National Research Council 1979[336]) that the local climate change response in a particular variable can differ substantially from the corresponding globally averaged response. For the latest versions of the geographical distributions of the response in particular variables to anthropogenic forcing, and the corresponding globally averaged response, the reader is referred to examples seen in Figures SPM.5, SPM.8, TS.6 of the IPCC AR6 WGI.[13,20]

Major Uncertainties and Research Gaps

Natural Variability

Because of the limited duration of the observational record, the magnitude of natural variability on decadal timescales and longer is not as well quantified as shorter-timescale variability. For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

Atmospheric Circulation Changes

While advances have been made in reconciling the previously reported differences in tropical expansion rates in observations and model simulations, uncertainties remain, especially in future projections of tropical expansion in the Northern Hemisphere because of the large natural variability and the relatively small poleward expansion in response to increasing GHGs.[90] Some studies also highlighted several important sources of uncertainty in projecting midlatitude atmospheric circulation changes related to model biases (e.g., Dong et al. 2021[58]), a tug-of-war between opposing mechanisms (e.g., Shaw and Voigt 2015[319]), and natural variability (e.g., Deser et al. 2020;[53] Dong et al. 2021[87]). For historical century-scale

regional trends in sea level pressure, large differences were found between different observational estimates from gridded datasets and reanalysis reconstructions.[323]

As discussed in KM 3.4, large-scale circulation changes are influenced by meridional and vertical temperature gradients; thus, Arctic amplification (the enhancement of near-surface air temperature change over the Arctic relative to lower latitudes), besides changes in the tropical Hadley circulation, may also influence midlatitude atmospheric circulations such as blocking, with potential implications for cold extremes. However, significant challenges remain in connecting Arctic amplification to midlatitude circulation changes due to the complex nonlinear dynamics of the jet stream.[337,338]

Water Cycle Changes

Of note is the role of climate variability in many aspects of the water cycle (especially for changes at the regional scale): natural variability is known (with *high confidence*, from observations, theory, and simulations) to be large for many aspects of the water cycle, and this can result in a low ceiling to the likelihood that can be placed on any specific realization of the future or past water cycle, even in situations where confidence in understanding is high (see above, "Large Ensemble Simulations" in KM 3.3, and Douville et al. 2021[201]). For this reason, it is particularly important for the water cycle to focus on the probability of what could happen in the future and the probability that observed changes that have already occurred are due to forced changes (as opposed to natural variability), rather than focusing on specific deterministic trajectories of what has already happened or will happen in the future. Furthermore, forced changes in variability that are expected for precipitation and other aspects of the water cycle complicate this picture further, more than for other variables such as temperature.

For extreme precipitation in particular, an outstanding question is whether, and if so how much, the thermodynamic and dynamic components of extreme precipitation change are coupled.[339] This would imply a positive feedback mechanism that could amplify extreme precipitation increases beyond the thermodynamic increase.

One uncertainty is the role of vegetation in modulating changes in evapotranspiration, which can in turn influence other factors including soil moisture, streamflow, and wildfire. In addition to changing evaporation from soil, plants also influence total evaporation through competing effects. In response to increased atmospheric CO_2 concentrations, plant stomata do not need to open as much to take in CO_2 for photosynthesis, which can reduce the amount of water they lose through transpiration, thus decreasing total evapotranspiration.[340] Conversely, an overall increase in the amount of vegetation can amplify evaporative losses and surface drying.[215,341,342] It is not yet clear which of these mechanisms will predominate, although model projections and observational analyses for the US suggest that the net effect will be for warming to increase evaporation and surface drying in much of the country.[199,200,207,208,343]

A key gap in understanding the hydrologic cycle and how it can change is the enormous range of scales in space and time on which relevant processes operate, from the scale of nanometers (cloud condensation nuclei), to the scale of cloud systems and watersheds (1 km to 1,000s of km), to the whole globe (evaporation and precipitation constitute a large fraction of energy flow between the surface and atmosphere). No observing system can capture, and no numerical model can represent, all of these processes at once, which is a key challenge for understanding and projecting the water cycle and its change. Continuing to increase the range of scales that can be captured by consistent, continuous observing systems and represented within a single model is one promising path toward decreasing some of the uncertainty in the future water cycle.[201]

Changes in the Carbon and Biogeochemical Cycles

Carbon fluxes, especially from the terrestrial biosphere are spatially heterogeneous and can undergo large temporal changes as well. Observations used to estimate carbon fluxes are sparsely distributed, and data records are often too short to be used to characterize interannual variability and trends. Models of ocean circulation and biogeochemistry and detailed models of plant growth and dynamics can be used to upscale carbon fluxes using observations for guidance, but there is significant uncertainty in many processes, such as the effects of nutrient limitation on plants and phytoplankton and responses to climate changes. Machine learning approaches have also been used to upscale flux observations (e.g., Jung et al. 2020[344]). Inverse modeling combines information from atmospheric observations, atmospheric transport models, and best-available estimates of carbon fluxes from land and ocean via models to produce carbon flux estimates; however, these modeling systems are also limited by sparse data. Major regions that are important for understanding the global carbon budget, such as the tropics and Siberia, do not have adequate observational coverage, and this lack makes accurate estimates of land and ocean fluxes difficult to achieve.

All of the above-mentioned issues, and the large uncertainty associated with future emissions, make predicting the future evolution of the carbon cycle difficult. Uncertainties in future climate drivers such as temperature, precipitation, and cloudiness result in uncertainty in how land and ocean biogeochemistry will evolve in the future. Furthermore, the difficulties in modeling nutrient availability and limitation, as well as disturbances such as fires, insect and disease outbreaks, severe weather, and human land-use change, introduce more uncertainties that affect predictions of how the carbon cycle and climate change will interact. The mobilization to the atmosphere of CO_2 and CH_4 from enhanced decomposition of the huge reserves of carbon in Arctic soils represents a potentially important positive carbon cycle–climate feedback, but it is particularly difficult to model due to difficult-to-quantify processes like cryoturbation and local erosion and thermokarst processes.[345] Current carbon cycle models that are coupled to climate models disagree widely on the future response of carbon exchanges between the oceans, land biosphere, and atmosphere to continued fossil fuel emissions. The range of responses has not appreciably changed since the previous model intercomparison (CMIP5).[134]

Changes in Ocean, Cryosphere, and Sea Level

Many of the components of the modern sea level observation network—particularly space-based platforms—are limited in their coverage of coastal regions. The US coastlines have better coverage from tide gauges than other parts of the world, although large gaps between tide gauges are still present. This is also true of measurements of coastal subsidence that generally originate from point-measurements from the Global Positioning System, although satellite-based interferometric synthetic aperture radar (InSAR) provides a possible solution (e.g., Shirzaei et al. 2021[346]). The connection between open-ocean sea level change and the sea level change experienced at the coast is still an active research area.

As a result of observations and improved modeling efforts, there is increased consensus regarding the behavior of many of the ice sheet processes. However, the future response of the ice sheets as the climate continues to warm, and of some of the associated processes, is still uncertain. It has been hypothesized that two possible processes in particular, known as the marine ice cliff instability[151,152] and the marine ice sheet instability,[153,155,156] could lead to rapid ice sheet loss over the course of several decades. The physical processes that would result in these instabilities and how they would progress once triggered remain uncertain. Resolving these uncertainties would require continued and additional observations of the ice sheets—and ocean and atmosphere that surround them. Additionally, advances in ice sheet modeling that potentially leverage these observations are a priority to narrow future estimates of ice mass loss.

Regional-Scale Changes

Although the idea that the regional climate change response differs from the globally averaged response is not controversial, there remain major uncertainties in the magnitudes of climate change responses at any given location. This reflects large differences in local outcomes across the GCM projections, as well as large differences in the local response when those GCMs are downscaled to higher resolution.

Description of Confidence and Likelihood

The section is a description of general results, so confidence and likelihood do not apply.

Key Message 3.5

Humans Are Changing Weather and Climate Extremes

Description of Evidence Basis

The theoretical basis of changes in extreme temperature and precipitation are well established. As temperature increases, a shift in the distribution implies that high temperatures become more frequent. Extreme precipitation occurs in saturated atmospheres. The Clausius–Clapeyron relationship, identified in the 19th century—specifying that saturation-specific humidity increases by between 6% and 7% per one degree Celsius of warming at typical surface air temperatures—dictates that available moisture during extreme storms increases with warming. The efficiency with which different types of storms precipitate that available moisture varies, as does the response in precipitation efficiency to warming. Limited event attribution studies and other high-resolution modeling studies find that extreme precipitation can increase at a rate greater than that indicated by Clausius–Clapeyron.

The effect of warming on drought varies between drought definitions. Understanding of changes in meteorological drought is limited by understanding of the atmospheric circulation changes that affect storm track and frequency. On the other hand, changes in agricultural drought are sensitive to changes in evapotranspiration, which increases sharply with increased temperatures.[221]

Major Uncertainties and Research Gaps

Land surface and vegetation processes have substantial impacts on climate extremes through the modulation of energy fluxes between the surface and atmosphere and surface water partitioning.[347] For example, dry surface conditions (e.g., a drought) and urbanization can both amplify heat extremes,[348,349] while wetter soils can increase the risk of precipitation events causing large floods.[350,351] However, few long-term data on these processes are available at large scales,[348] and their representation in climate models is often highly simplified.[352] Further, despite the fact that many extremes are strongly tied to atmospheric circulation anomalies (e.g., atmospheric ridge events), changes in these dynamics remain highly uncertain. While changes in sea ice and meridional temperature gradients may be linked to increases in the frequency and persistence of midlatitude circulation patterns associated with extreme events (e.g., Coumou et al. 2018[353]), studies suggest that these changes have not yet emerged from background natural variability.[354] Confidence in model-based assessments of changes in frequency or intensity of extreme events can be enhanced in cases where a detectable anthropogenic trend in an extreme, or closely related metric, has been found. However, this is not the case for some extreme event types, including those related to long-term changes in circulation.

The ensembles of tropical cyclone–permitting (~20 km) model simulations are small both in the number of realizations and of independent climate models, which limits understanding of tropical storm statistics. Even fewer long convection–permitting (<4 km) regional model simulations are available, limiting our understanding of how mesoscale convection systems and similar intense storms will respond to warming.

The effect of warming on the processes leading to rapid intensification is also poorly understood. While theory and high-resolution modeling find that winds in the most intense storms become stronger, detection and attribution of such changes has not yet been accomplished, as the most common metric—the Saffir–Simpson wind speed—is an instantaneous point-wise maximum and very noisy.

Finally, climate change may be moving us into an era of large or unprecedented extremes that fall far outside the range of historical variability, particularly regarding temperature (e.g., Overland 2021[355]). In such cases, many statistical approaches may be insufficient and make it difficult, with any confidence, to conduct detection and attribution analyses.[76]

Description of Confidence Likelihood

Anthropogenic forcing has increased the frequency, duration, and intensity of extreme heat across most land areas (*high confidence*),[20,356] with some evidence that extreme cold events have also declined (*medium confidence*).[308] These changes are driven by average shifts in the temperature distributions toward warmer conditions that are significant and robust across most of the world.[180] Heavy precipitation events have increased in some regions (*high confidence*)[20] because of the strong dependence of the water-holding capacity of the atmosphere on temperatures (e.g., Kunkel et al. 2013[357]). Coastal flood risk has increased, and is projected to continue to increase, because of sea level rise (*high confidence*; e.g., Vousdoukas et al. 2018[358]). Notably, while the most extreme river floods are expected to increase in severity because of increases in heavy precipitation (*high confidence*), more general trends are mixed because flood risk also depends on policies and land surface processes.[201] Soil moisture droughts are also increasing in frequency and severity in many regions (*medium* to *high confidence*)[20] through the direct effects of warming on snow, evapotranspiration, and plant water use.[43,215,342] There is also *high confidence* that the intensity and frequency of precipitation droughts are increasing in Mediterranean-climate regions.[359,360,361,362] Climate change increases fuel flammability through higher temperatures and lower humidity and has increased the area burned by wildfires in western US (*high confidence*)[217,219] and Australia.[363] Despite these climate change–driven regional increases, however, global burn area has declined in recent years as a consequence of agricultural expansion and intensification, especially in savanna and grassland ecosystems.[364]

While tropical cyclones are the most studied extreme storm type with high-resolution (~25 km) global models, more such simulations are required to develop a theory about cyclogenesis and intensity changes with climate change. While attribution studies find that extreme precipitation over land in major tropical cyclones *very likely* scales with temperature increases at rates greater than the Clausius–Clapeyron rate, average total tropical storm precipitation scales at least at Clausius–Clapeyron rates,[42] but confidence is limited as there are limited high-resolution projections. It is also *likely* that precipitation increases over land will differ from those over oceans.

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Fifth National Climate Assessment: Chapter 4

Water



Chapter 4. Water

Authors and Contributors

Federal Coordinating Lead Author

Ariane O. Pinson, US Army Corps of Engineers

Chapter Lead Author

Elizabeth A. Payton, University of Colorado Boulder, Western Water Assessment

Chapter Authors

Tirusew Asefa, Tampa Bay Water

Laura E. Condon, University of Arizona

Lesley-Ann L. Dupigny-Giroux, University of Vermont

Benjamin L. Harding, Lynker

Julie Kiang, US Geological Survey

Deborah H. Lee, NOAA Great Lakes Environmental Research Laboratory

Stephanie A. McAfee, University of Nevada, Reno

Justin M. Pflug, University of Maryland, College Park, Earth System Science Interdisciplinary Center

Imtiaz Rangwala, University of Colorado Boulder, North Central Climate Adaptation Science Center

Heather J. Tanana, University of Utah, S.J. Quinney College of Law

Daniel B. Wright, University of Wisconsin–Madison

Technical Contributors

Frances V. Davenport, Colorado State University

Andrea L. Taylor, Indian Health Service

Review Editor

Beth M. Haley, Boston University, School of Public Health

Cover Art

Jon Bradham

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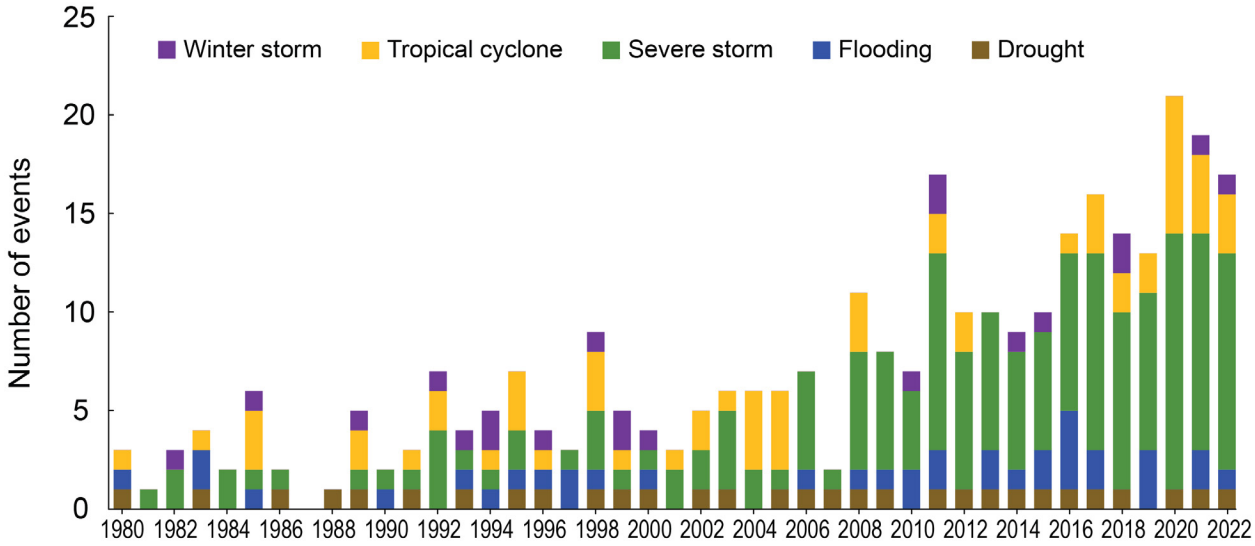
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Introduction

Climate change is intensifying rainfall and floods, deepening droughts, and shifting weather patterns across the globe,[1] causing profound effects on terrestrial freshwater supplies and quality. Rising sea levels, reduced snowpacks, shrinking rivers, and declining groundwater threaten cities and rural communities and endanger forest, riverine, and other ecosystems across the United States.

Climate change, combined with greater exposure and vulnerability, is increasing the frequency of water-related disasters in the US (Figure 4.1).

Water-Related Billion-Dollar Disasters in the United States

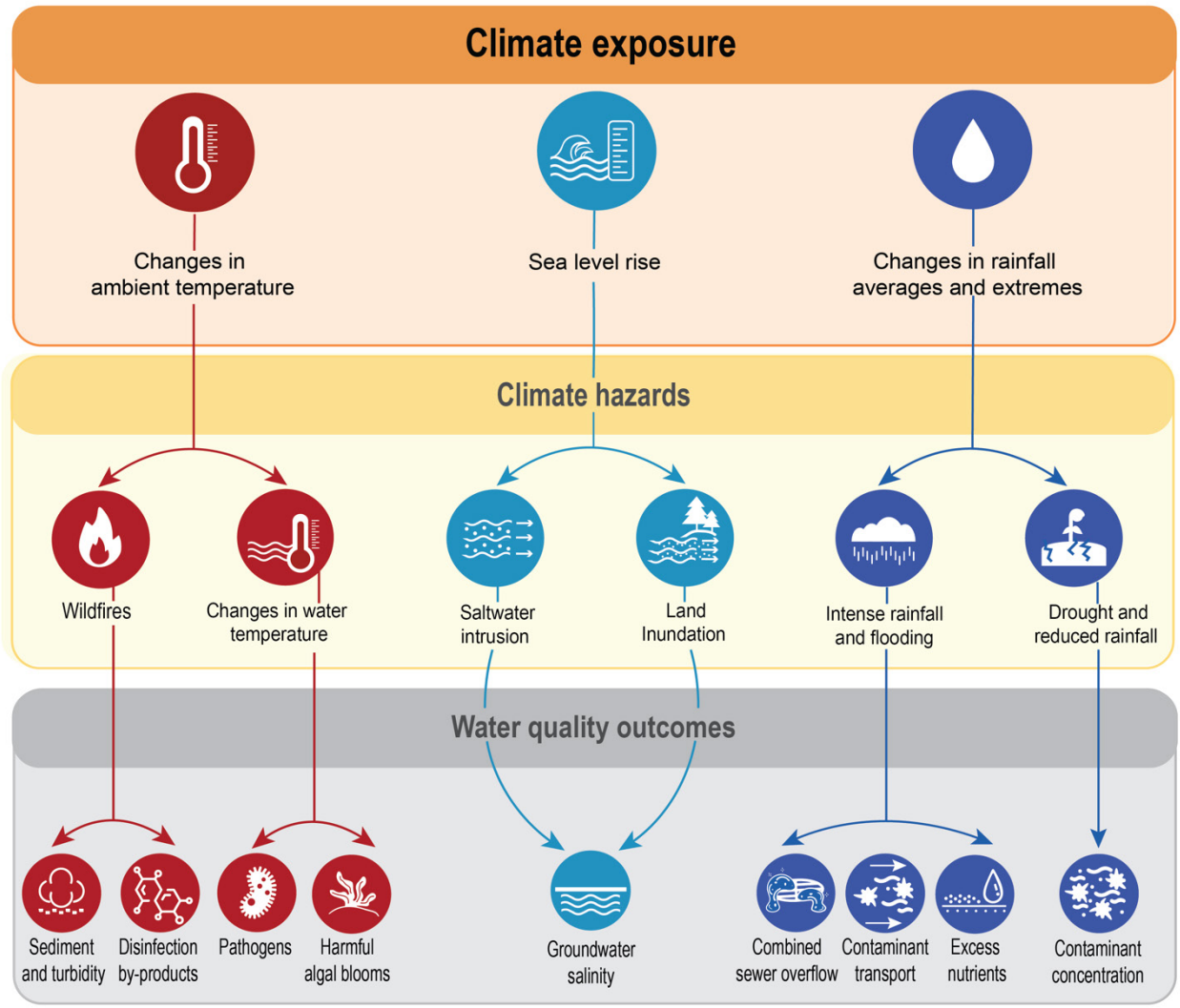


Water-related billion-dollar disasters are increasing in the United States.

Figure 4.1. Across the US, the number of water-related disasters with damages exceeding $1 billion (adjusted for inflation) during 1980–2022 rose due to increases in exposure, or assets at risk; vulnerability, or how much damage a hazard of a given intensity causes; and climate change-driven increases in the frequency of extremes. Adapted from NCEI 2023.[2]

While these events are primarily related to water *quantity*, impacts related to water *quality* are increasing as well, as predicted in the Fourth National Climate Assessment, released in 2018 (NCA4).[3] Temperature increases, sea level rise, and changes in precipitation are expected to continue to degrade water quality for people and ecosystems (Figure 4.2; KMs 4.2, 15.1, 15.2).[4,5,6]

Climate Change Impacts to Water Quality



Climate change threatens the quality of freshwater supplies.

Figure 4.2. Changes in ambient temperature, sea level, and rainfall (**top**) can create climate-related hazards, such as changes in water temperature and saltwater intrusion (**middle**) that can have negative impacts on water quality (**bottom**). Saltwater intrusion is an imminent threat to coastal and island communities dependent on groundwater for drinking water (KMs 30.1, 9.2); agricultural areas face risks to water supplies when fertilizers and pesticides are mobilized by flooding;[7] higher temperatures are putting many areas at risk of exposure to harmful algal blooms (e.g., KM 22.2) and increases in fecal coliform bacteria;[6] and treatment plants are challenged by sediments and debris from wildfires in their source waters (KM 6.1).[8,9] Adapted from Nijhawan and Howard 2022[6] [CC BY 4.0].

Climate change is forcing a reexamination of our concepts of rare events. Extreme precipitation incidents are more intense and more frequent (KM 2.2); extended droughts in the West appear to be due in part to long-term aridification in addition to episodic drying (KM 4.2); and compound hazards are increasing as the events that combine to create them become more frequent (Focus on Compound Events).

The US is slowly adapting to these changes. Utilities are exploring ways to integrate change into planning, and communities are cooperatively seeking solutions to water shortages and flooding (KM 4.3). But barriers arise from legal and regulatory institutions that have been in place for decades or even centuries, locking in practices that hinder adaptation (KM 4.3). The Nation's aging water infrastructure, designed under

regulations and standards appropriate to an unchanging climate, is deteriorating and threatening public health, a situation little changed since it was highlighted in NCA4 (KM 4.2).[3]

Perhaps the most notable advance in recent years is the growing recognition of environmental injustices exacerbated by climate change (KM 1.2). Overburdened populations, including Black, Hispanic, Indigenous, Tribal and other communities, are suffering disproportionate impacts from climate-driven water quality and quantity hazards that threaten these communities' water security (KMs 4.2, 15.1, 15.2, 16.1).

The Nation is making some progress. The tools and data needed to support water resources planning and management have become more sophisticated and widely available, though gaps remain, particularly hydrologic projections for the US Caribbean, Hawai'i, and the US-Affiliated Pacific Islands, where water security concerns are high (KM 4.1; Box 23.2). Gaps in local projections of extreme event frequencies, magnitudes, and durations also hinder adaptation. There has been enormous growth in the availability of science-based climate information for water providers and natural resource managers, demonstrating increasing awareness and demand for solutions. These and similar efforts are the first steps toward building resilient human and natural systems in the face of climate-induced changes to the water cycle.

Key Message 4.1

Climate Change Will Continue to Cause Profound Changes in the Water Cycle

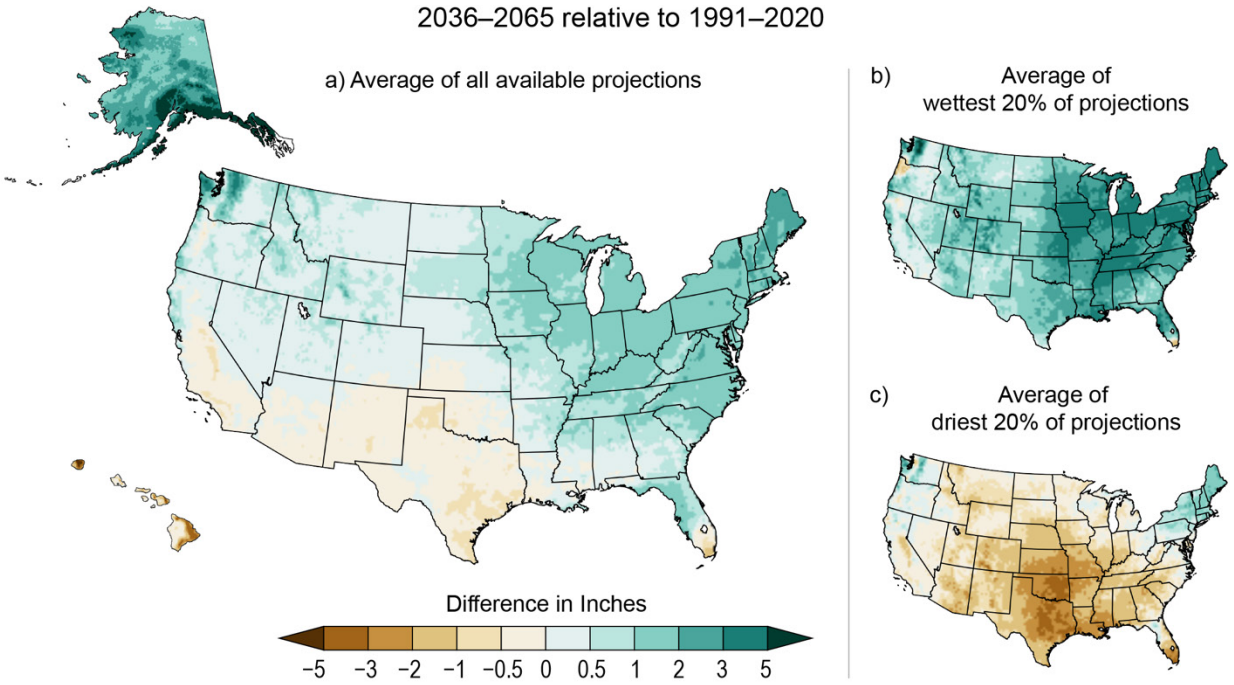
Changes to the water cycle pose risks to people and nature. Alaska and northern and eastern regions of the US are seeing and expect to see more precipitation on average, while the Caribbean, Hawai'i, and southwestern regions of the US are seeing and expect to see less precipitation (*medium confidence*). Heavier rainfall events are expected to increase across the Nation (*very likely*, *very high confidence*), and warming will increase evaporation and plant water use where moisture is not a limiting factor (*medium confidence*). Groundwater supplies are also threatened by warming temperatures that are expected to increase demand (*very likely*, *high confidence*). Snow cover will decrease and melt earlier (*very likely*, *high confidence*). Increasing aridity, declining groundwater levels, declining snow cover, and drought threaten freshwater supplies (*medium confidence*).

Freshwater availability is affected by the quantity of water in storage, the timing of water movement, how much water is used, and its quality,[10] all of which are governed by the interrelated hydrologic components of the water cycle. Changes to these components are occurring across the Nation as a result of human activities as well as human-caused climate change. These changes are superimposed on natural variability, resulting in changes to both water availability and water-related hazards (KMs 2.1, 2.2).

Precipitation Changes

Climate change has already shifted precipitation patterns across the country, including increased variability and elevated likelihood of extreme rainfall events (KMs 2.2, 3.5). These trends exhibit substantial regional and seasonal variations (KM 2.2).[11] Projected changes in annual precipitation also exhibit large regional differences (Figure 4.3). Precipitation trends and projections are discussed in more depth in Chapters 2 and 3.

Projected Changes in Annual Precipitation by Midcentury



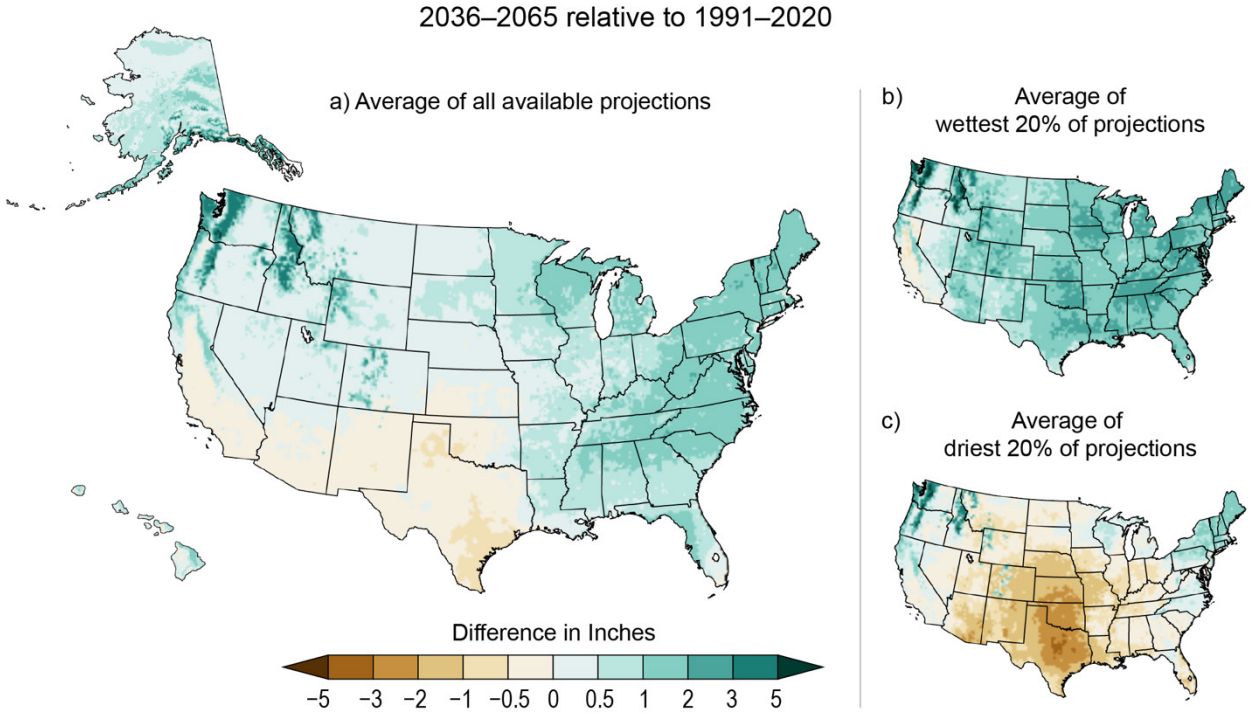
Annual precipitation projections show large regional differences.

Figure 4.3. Under an intermediate (RCP4.5) scenario, annual precipitation is projected to increase for much of the US (**a**), except for the Southwest, Hawai'i, and the US Caribbean (not shown; see Figure 23.2, which shows rainfall reductions of about 10% by midcentury, and increases in dry days during the wet season, for Puerto Rico). The wettest and driest 20% of projections (**b**, **c**) illustrate the range of uncertainty in annual precipitation projections. This figure shows projected changes in inches. In the Southwest, a half-inch change in annual precipitation has more influence on the region's hydrology than does a half-inch change in the Northeast (see Figure 2.10 for percent changes under different warming levels). Projections are not available for the US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Evapotranspiration Changes

Evapotranspiration is water that evaporates from soil, snow, and surface water or transpires from plants. It is a key component of the water budget and drives irrigation water demand. Increases in temperature and changes in other climate variables alter the evaporative demand (or potential evapotranspiration). In recent decades, evaporative demand has increased in much of the West, with few apparent trends in the East.[12] Actual evapotranspiration is evaporative demand limited by water availability. In the continental US, actual evapotranspiration has trended lower in the Southwest as water availability has declined, while the East and North show an increase. The greatest increase in actual evapotranspiration has been in the South from eastern Texas to northern Florida.[11,13] These trends are largely projected to continue with climate change (Figure 4.4).

Projected Changes in Annual Actual Evapotranspiration by Midcentury



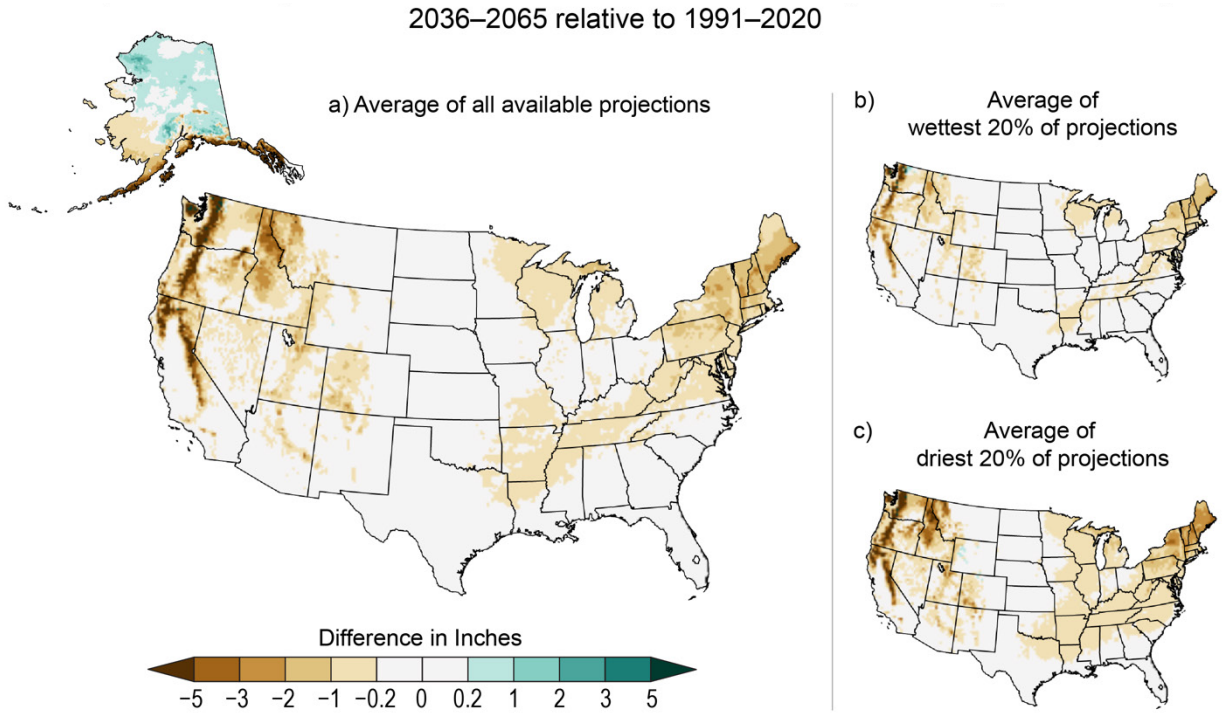
Actual evapotranspiration is projected to increase across most of the Nation but decrease in the Southern Great Plains and Southwest.

Figure 4.4. Actual evapotranspiration is the water that evaporates from soil and surface water or transpires from plants. Higher rates of evapotranspiration can reduce overall water availability even if precipitation does not change; conversely, low water availability can limit actual evapotranspiration. Under an intermediate scenario (RCP 4.5), actual evapotranspiration is expected to decrease in regions with decreasing or unchanging precipitation (**a**), such as the US Southwest, the Southern Great Plains, and the Caribbean (not shown; Box 23.2). Wetter regions, including the Northwest, Alaska, and the eastern half of the US, will see higher actual evapotranspiration. The wettest and driest projections (**b, c**) illustrate the range of uncertainty. Projections are not available for the US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Snow and Glacier Changes

Snow is a natural reservoir, storing cold-weather precipitation and later releasing water through snowmelt. With higher temperatures, the fraction of precipitation falling as rain instead of snow will increase.[14,15] Warming will also cause earlier snowmelt,[14,16] altered rates of snowmelt and evaporation directly from the snow,[17,18,19,20] and longer snow-free periods.[21,22] Most historical snow-observation records already show trends toward earlier peak snowpack, smaller volumes, and decreasing snow-season duration (Figure A4.7),[11] particularly for warmer maritime and lower-elevation regions.[23,24,25] In areas of the West where snow is the dominant source of runoff,[26] total seasonal snow water volume is projected to decrease by more than 24% by 2050 under intermediate (RCP4.5; Figure 4.5) and higher scenarios, with persistent low-snow conditions emerging within the next 60 years.[24] These snow reductions, combined with projected increases to water demand, are expected to stress water supplies, particularly in the West (KM 28.1), where snowmelt supplies a disproportionate amount of water for municipal water supplies and agriculture.[27,28,29] Reductions in snow cover are also accelerating the retreat of glaciers[30,31,32] that are critical for summer streamflow in Alaska[33] and the Pacific Northwest (Ch. 27).[34]

Projected Changes in Maximum Annual Snow Water Equivalent by Midcentury



Continued decreases in snowpack water content are projected across much of the US.

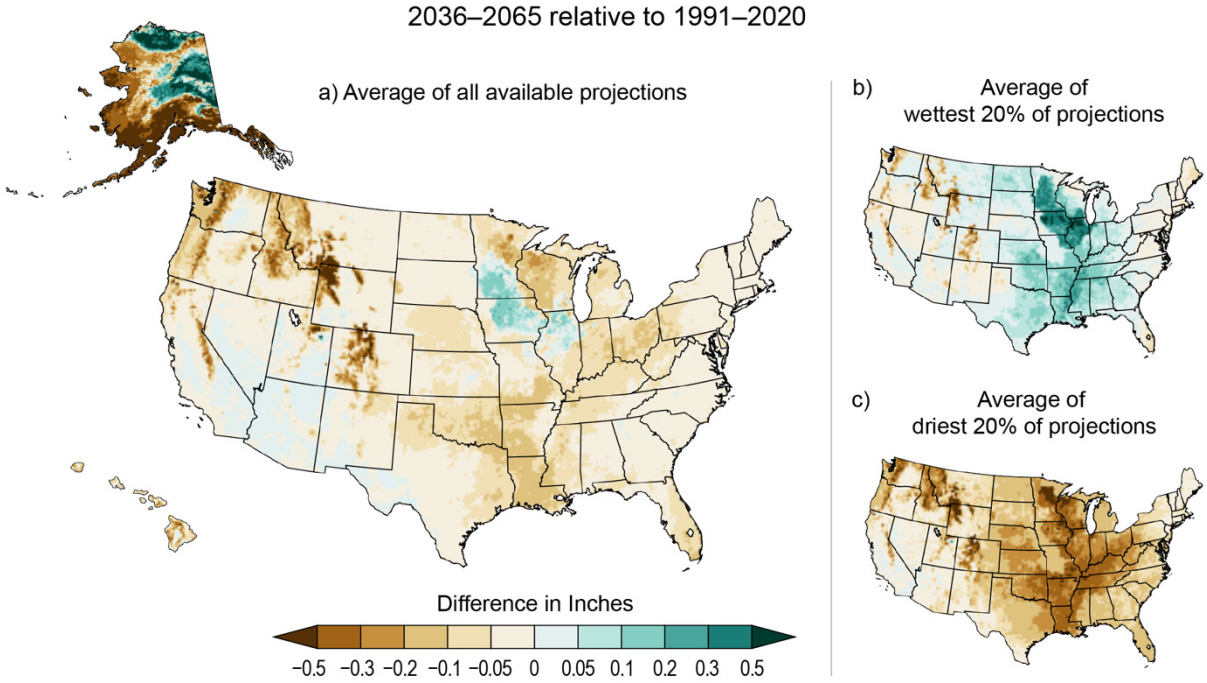
Figure 4.5. Snow water equivalent (SWE), the quantity of water stored in the snowpack, is key to regional water supplies. Under an intermediate scenario (RCP 4.5), peak SWE is projected to decline across much of the country except for some high-elevation interior locations in the contiguous United States and parts of Alaska (**a**). The largest snowpack declines are expected in warmer snow climates like coastal southern Alaska and the mountain ranges of California and the Northwest. The wettest (**b**) and driest (**c**) projections both show decreases in SWE, reflecting the influence of warming on future snowpack. Snow on the highest Hawaiian mountain peaks has important cultural and ecological significance, but projections at this resolution are not available. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Soil Moisture Changes

Soil moisture is water stored in the soil, usually close to the surface. It is a key component of the water cycle, supporting agriculture and ecosystem productivity, modifying streamflow by absorbing precipitation and snowmelt, and modulating climate.[35,36] A scarcity of soil moisture observations[37] has led to uncertainty regarding overall amounts, seasonality, and the direction of changes; however, there is consensus that soils are becoming drier in the Southwest.[38,39,40,41]

Projections suggest that summer soil moisture will decrease across most of the country (Figure 4.6), with parts of the upper Midwest and Alaska[42] as exceptions. The Northwest, parts of the central and eastern US, and Alaska can expect seasonal changes in total soil moisture, with wetter soils in winter.[42,43] Summer soil moisture in the Southwest could increase if summer precipitation is higher, but there is greater confidence in decreasing annual soil moisture in the region (Figure 2.4).[38,43]

Projected Changes in Average Summer (June–August) Soil Moisture by Midcentury



Projected decreases in summer soil moisture will have important implications for agriculture and ecosystems.

Figure 4.6. Summer soil moisture supports dryland agriculture and ecosystem functions and reduces irrigation demand and wildfire risk. Under an intermediate scenario (RCP 4.5), soil moisture is projected to decrease during the summer months (June, July, and August) for most of the country (**a**), with the West seeing decreases even under the wettest projections. Exceptions include portions of the Upper Midwest and Alaska. The range between the wettest (**b**) and driest (**c**) projections illustrate the uncertainty in summer soil projections. Projections are not available for the US Caribbean or US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Groundwater Changes

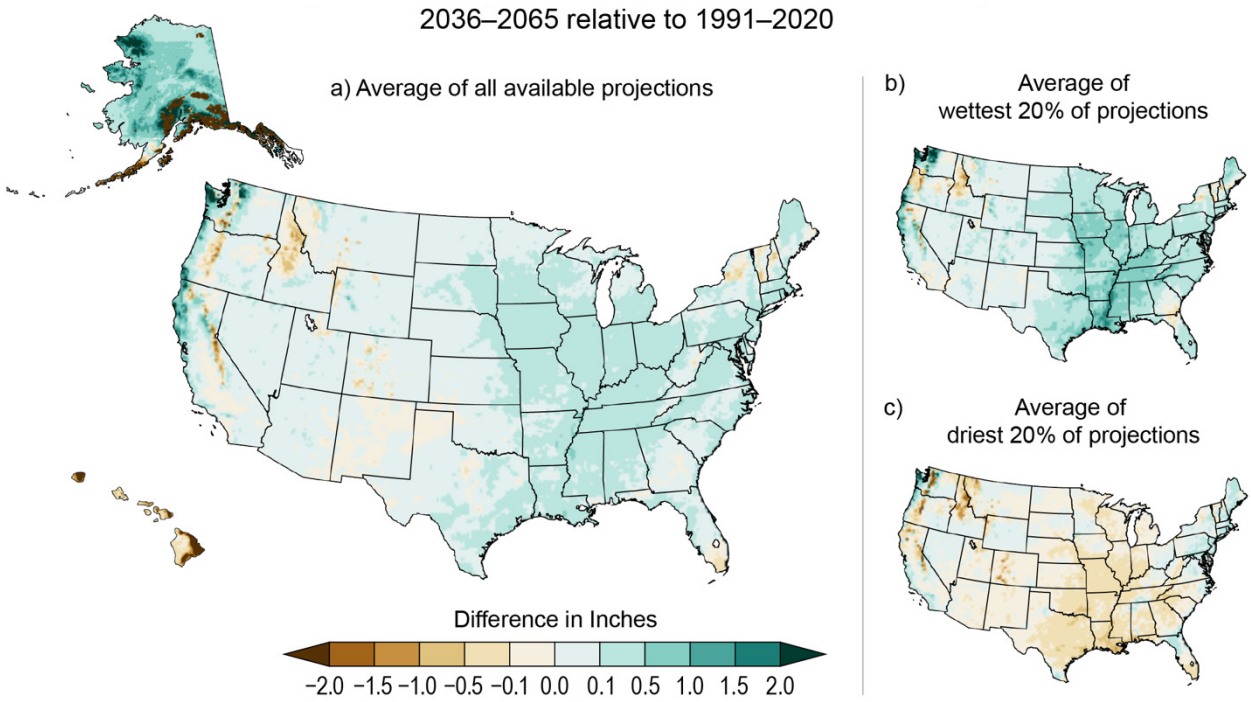
Groundwater is water stored below the land surface; it can be close to the surface or extend hundreds of feet deep. It is a crucial water supply for human systems and can moderate changes in temperature and precipitation.[44,45,46] NCA4 noted that groundwater depletions can increase drought risk and highlighted unsustainable groundwater usage and the likelihood of further declines in the future.[3] More recent work has emphasized the hydrologic connections between surface and groundwater that make surface water systems vulnerable to declining groundwater levels.[47,48]

Groundwater trends vary regionally and are difficult to project because the intensity of both groundwater withdrawals and recharge depends on human factors (e.g., land use, population, surface water allocations, and groundwater regulation) in addition to climate drivers.[49] Natural groundwater recharge varies from year to year but is projected to decrease slightly in the Southwest and increase slightly in the Northwest.[50,51] Higher temperatures will increase irrigation demand (Figure 4.9), which can lead to increased groundwater pumping in areas where groundwater is the primary water supply or where surface water supplies are limited.[52,53,54] Groundwater levels have already been declining in many major aquifers due to lack of management, overpumping, and decreased recharge; increased pumping could accelerate long-term storage losses, but those impacts will depend on the regional factors noted above.[49,52,55,56] Groundwater declines caused by increased drought severity and duration in the future are a concern in many parts of the country (KMs 23.3, 24.5, 28.1; Ch. 26).

Runoff Changes

Changes to the water cycle components discussed above combine with other factors to affect runoff (surface water flow). For example, snowpack changes impact the seasonality of runoff in snowmelt-dominated areas,[57] while soil moisture affects the amount of precipitation and snowmelt that becomes runoff.[58] In addition to direct precipitation and groundwater, runoff is a primary source of water supply for people and ecosystems. Annual runoff trends for the most part have tracked annual precipitation trends. Similarly, the trend toward increasing annual runoff variability in most of the eastern half of the US is consistent with increasing extreme precipitation events there.[11] Increases in heavy precipitation events are projected to increase annual runoff over much of the US (Figure 4.7).[59,60]

Projected Changes in Annual Runoff by Midcentury



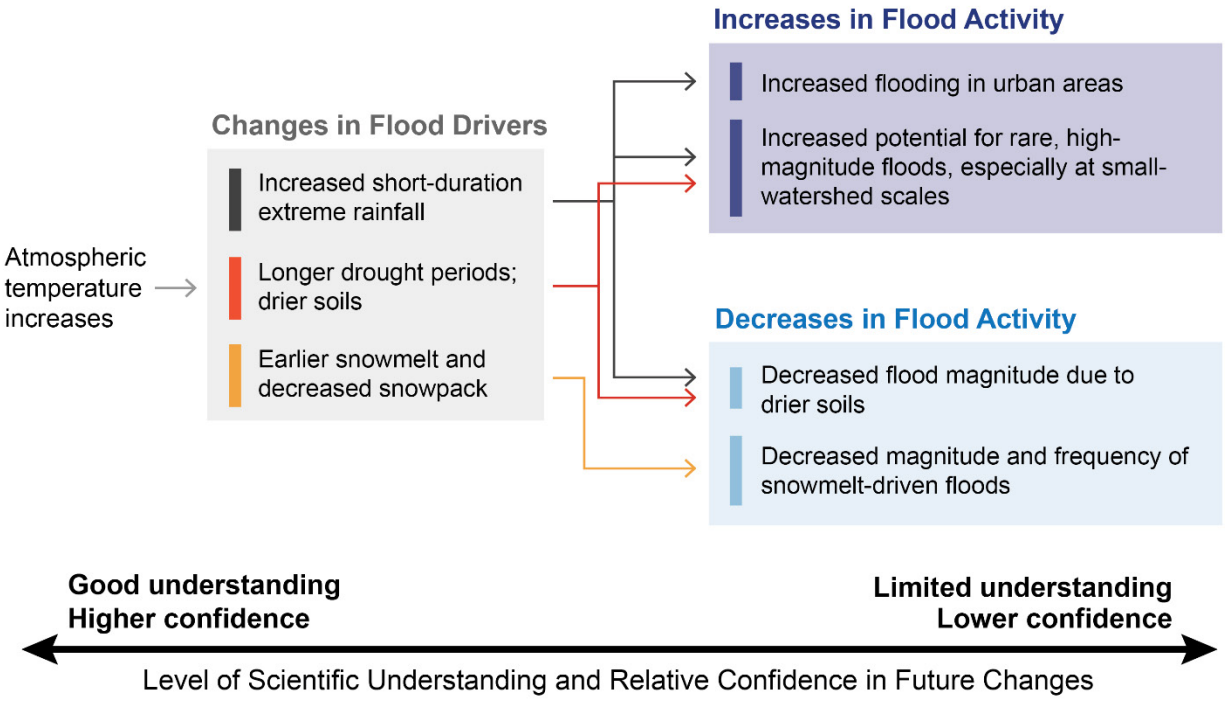
Projected changes in runoff vary across the Nation due to projected changes in multiple aspects of the water cycle.

Figure 4.7. Rivers and streams aggregate runoff across watersheds, and runoff integrates climate change impacts to the water cycle (Figures 4.3, 4.4, 4.5, 4.6); as a result, impacts to runoff over a watershed are commonly used as surrogates for impacts to streamflow. Under an intermediate scenario (RCP4.5), projections of annual runoff vary geographically depending on relative changes to precipitation, evapotranspiration, snow and ice, groundwater, and soil moisture. Decreases are projected in Hawai'i and parts of the Nation supplied by snow (**a**). Projections are not available for US-Affiliated Pacific Islands or the US Caribbean; however, given projected decreases in precipitation and increases in temperature in the Caribbean, annual runoff is expected to decrease. The range between the wettest (**b**) and driest (**c**) projections illustrate the uncertainty in runoff projections. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Extreme Events: Floods and Droughts

Inland floods are driven by complex interactions among precipitation amount and timing, soil moisture, snowpack, and land cover (see KM 9.1 for coastal flooding). However, estimates of events such as the 100-year flood typically rely on historical observations and assumptions of an unchanging climate.[61] Methods that account for the added uncertainty of climate change are needed for infrastructure design, land use planning, and other purposes,[62,63,64] but future flood frequency is challenging to predict (Figure 4.8).[65,66] For example, some extreme precipitation events will be buffered by future reductions in soil moisture, which will allow more rainfall to be absorbed,[67,68,69] and some areas are projected to see increases in floods from rain falling on snow,[70,71] precipitation on wildfire-disturbed land,[72,73] and loss of natural water storage in urban landscapes.[74]

Climate Change Impacts to Inland Flood Drivers and Flood Activity

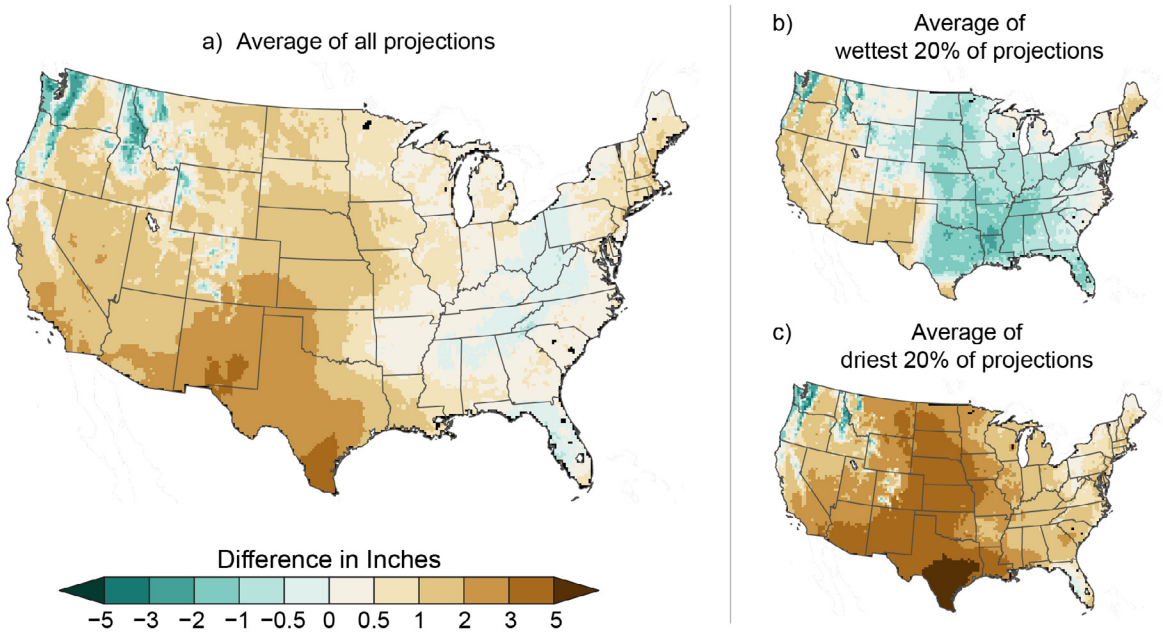


Climate change may cause both increases and decreases in inland flooding, depending on the location and time of year.

Figure 4.8. Inland floods result from combinations of factors, primarily extreme rainfall, soil moisture, and snowpack and snowmelt conditions. Each of these are subject to substantial variability and change across a wide range of timescales, from daily to decadal, in a warming climate. Scientific confidence in how the climate drivers of flooding will change is higher than in how those drivers will combine to affect floods in particular locations and seasons. Adapted from Yu et al. 2020[66] [CC BY-NC 4.0].

Changes in future precipitation and temperature are expected to exacerbate drought across large portions of the US.[75] Observed trends in drought (Figure A4.9) and climatic water deficit reflect these changes,[13] as do projections, with the strongest drying signal occurring in the Southwest (Figure 4.9).[76]

Projected Changes in Annual Climatic Water Deficit by Midcentury



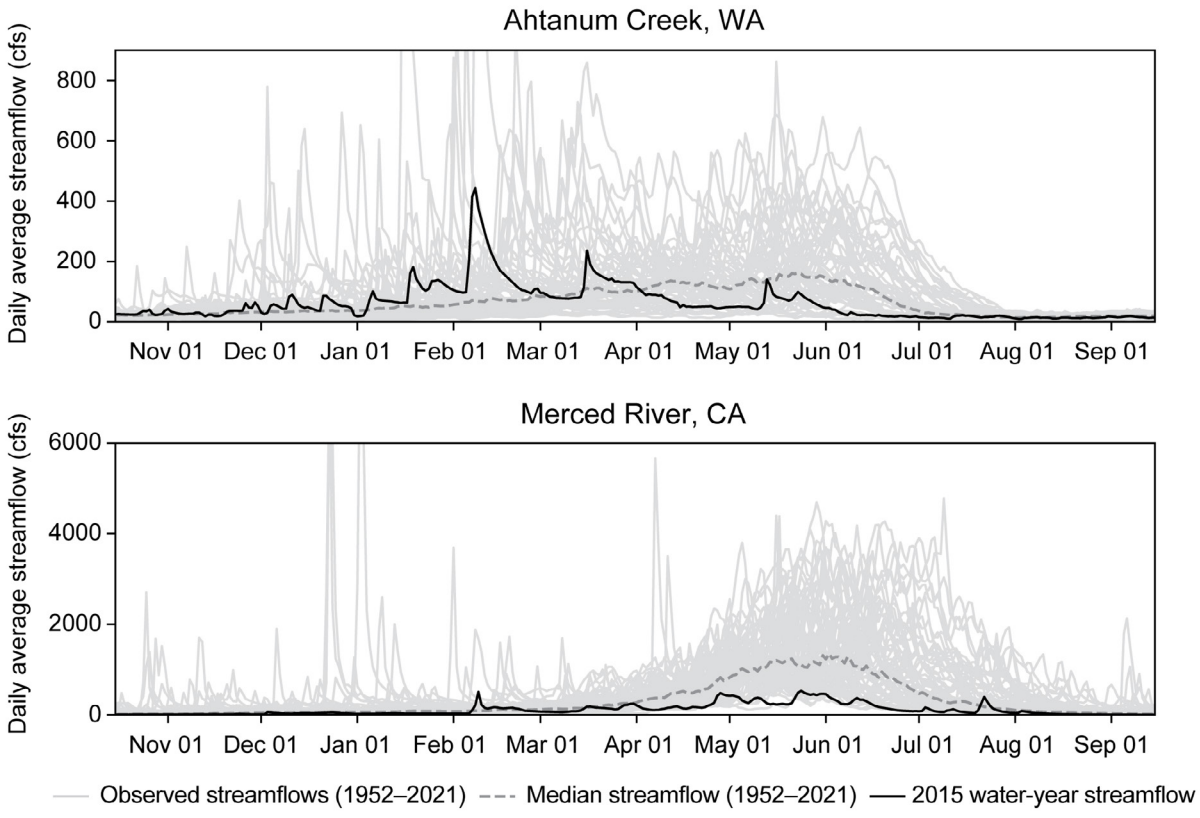
Water shortages to vegetation will increase across most of the Nation.

Figure 4.9. Climatic water deficit (CWD) is the shortfall of water necessary to fully supply vegetation requirements—CWD is zero if those needs are met, and a higher number indicates drier conditions. Vegetation water needs will increase with increases in temperature; as a result, in the absence of compensating increases in precipitation, CWD is projected to increase. Under an intermediate scenario (RCP4.5), CWD is expected to rise across much of the Nation, with the Great Plains and Southwest seeing the greatest increase (**a**, **c**). Even the wettest projections show increases in CWD in the West (**b**). Projections are not available for the US Caribbean, Alaska, Hawai'i, or US-Affiliated Pacific Islands; however, given expected temperature increases and annual precipitation decreases in Hawai'i and the US Caribbean, CWD is expected to increase in those regions, while Alaska is expected to see both increases and decreases similar to the pattern seen in the Northwest. Figure credit: University of Colorado Boulder.

Box 4.1. Washington–California 2015 Snow Drought

Snow droughts occurred across much of the western coastal mountain ranges during the 2014/15 winter. However, the climatic causes of these droughts varied. Western Oregon and Washington experienced a *warm* snow drought, wherein wintertime precipitation was 77%–113% of normal but elevated temperatures caused a larger proportion of that precipitation to fall as rain, which reduced snow accumulation and increased winter snowmelt.[15,77] As a result, wintertime streamflows were normal to high, but April to August flows were lower than normal (Figure 4.10).

Washington–California Snow Drought



In 2015, parts of Oregon and Washington experienced a warm snow drought while the California Sierra Nevada experienced a dry snow drought.

Figure 4.10. The timelines compare the 70-year (1952–2021) median streamflow (dashed line) with the 2015 water-year (October 2014–September 2015) streamflow (black line). Annual observed streamflows are also shown for 1952–2021 (gray lines). Values are daily average streamflows in cubic feet per second. Streamflow in summer 2015 was abnormally low, resulting from reduced snowpack during a warm snow drought (Ahtanum Creek) and a dry snow drought (Merced River). Daily streamflow is in cubic feet per second for each of the years 1952–2021 (gray lines). Merced River flows are lower year-round because of low total precipitation and little snowfall; Ahtanum Creek flows are shifted from summer to winter in 2014/15 because it was too warm for snow accumulation. Figure credit: University of Maryland, College Park and Lynker.

By contrast, the California Sierra Nevada experienced a *dry* snow drought, resulting in the shallowest snow volume ever recorded there.[15,78,79] Both the dry and warm droughts caused strain on water rights holders. In Oregon and Washington, irrigated crops—including valuable orchard crops—that depend on direct streamflow diversion water rights failed (Figure 4.11), but municipal water supplies that relied on storage rights that allow reservoirs to capture winter runoff were sufficient.[80] In California, total water supply was limited, resulting in severe or complete cutbacks to junior water rights and contract holders.[81]

Washington Apple Orchard Under Drought Stress



An apple orchard in the Roza Irrigation District in Washington shows extreme drought stress in September 2015.

Figure 4.11. This apple orchard suffered the effects of a warm snow drought the previous winter. The warm winter temperatures caused much of the precipitation to fall as rain instead of snow, producing a reduced snowpack, and led to early snowmelt, resulting in low streamflows during irrigation season. Photo credit: © Sonia A. Hall.

Key Message 4.2

Water Cycle Changes Will Affect All Communities, with Disproportionate Impacts for Some

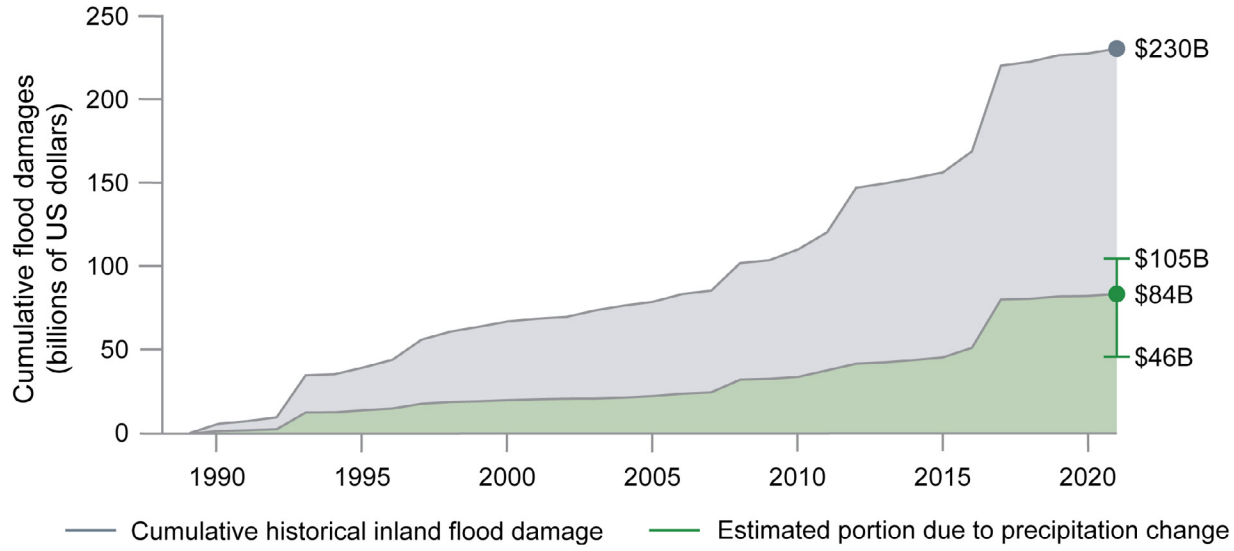
Natural and human systems have evolved under the water cycle's historical patterns, making rapid adaptation challenging. Heavier rainfall, combined with changes in land use and other factors such as soil moisture and snow, is leading to increasing flood damage (*likely, high confidence*). Drought impacts are also increasing (*medium confidence*), as are flood- and drought-related water quality impacts (*medium confidence*). All communities will be affected, but in particular those on the frontline of climate change—including many Black, Hispanic, Tribal, Indigenous, and socioeconomically disadvantaged communities—face growing risks from changes to water quantity and quality due to the proximity of their homes and workplaces to hazards and limited access to resources and infrastructure (*very likely, high confidence*).

Changes to the water cycle have manifold effects beyond those described in this chapter. See the Energy (Ch. 5), Ecosystems (Ch. 8), Agriculture (Ch. 11), Built Environment (Ch. 12), Transportation (Ch. 13), and Human Health (Ch. 15) chapters for more information.

Flood Impacts

Floods have important roles in creating and maintaining aquatic habitat, in regulating the reproductive cycles of fish and other river organisms, and in replenishing soil and nutrients in floodplains. Land-cover changes have limited these positive impacts and even exacerbated some of the negative consequences of floods. Climate change–driven changes in precipitation amount and duration, snowpack/snowmelt, and soil moisture have combined with land-cover change and increasing property values to increase overall economic damages from floods (Figure 4.12).[82]

Flood Damages Associated with Precipitation Change



A portion of observed increases in inland flood damages can be attributed to changes in precipitation.

Figure 4.12. Cumulative inland flood damages (in 2021 dollars) across the contiguous US (gray) and estimated portion due to changes in precipitation (green) are shown for 1988–2021. Over this period, heavy precipitation has increased over most of the US due to climate change (see Figure 2.8 for heavy precipitation changes over the 1958–2021 period). Error bars (in green) show the plausible range of cumulative damages in 2021, calculated using a 95% confidence level. Roughly 20%–46% of increases in observed flood damages can be attributed to increasing precipitation (assuming the same historical development patterns over the period 1988–2021). Other important contributors to flood damage include urbanization and land-use change, which can exacerbate runoff, and growth in the number and value of flood-affected buildings and other assets. Adapted from Davenport et al. 2021.[82]

In urban settings, pavements, roofs, and compacted soils do not absorb water as effectively as natural landscapes, amplifying the effects of heavy precipitation and concentrating flooding. In rural settings, lower amounts of impervious land cover allow soils to hold more rainfall. However, intensive agriculture can reduce the infiltration and water-holding capacity of soils and increase runoff, resulting in flooding.[83]

At major watershed scales, flooding along large river and lake systems causes numerous disruptions, including to rail, roadway, and river transportation; agricultural production; commodity deliveries; and industrial production, as seen during the Mississippi River flood of 2011 (KM 24.4).[84]

Increasing flood activity threatens water quality and ecosystems (Figure 4.2). As floodwaters inundate normally dry areas, they transport debris, chemicals, bacteria, and other contaminants (KM 23.1).[85,86] Heavy precipitation events are overwhelming aging combined stormwater–sewer systems, leading to discharges of contaminated water and raw sewage into receiving waters.[87,88] The upward trajectory of urban flooding impacts will likely continue with changing rainfall patterns and intensity.[89] Groundwater-sourced drinking water is becoming contaminated from standing floodwaters over wellheads and percolation into well-fields,[90] and in farmlands high runoff is discharging fertilizer into streams and lakes, causing harmful algal blooms.[91]

Drought Impacts

Droughts are driven by many factors, including unsupportable societal demands for water.[92] From a climate perspective, below-normal precipitation is a primary driver of drought, but there is growing acknowledgement that higher temperatures can cause drought to develop or become more intense than would be expected from precipitation deficits alone; higher temperatures drive increased atmospheric demand for moisture—a phenomenon known as hot drought.[75,93,94,95] Above-normal temperatures also contribute to snow drought (Box 4.1) and flash drought, which develops quickly over a few weeks.[96,97] Megadroughts are events of extraordinary duration and severity,[98] and many are documented in paleoclimate records.[99,100] Temperature's contribution to drought makes it clear that warming associated with climate change could increase the frequency, severity, and/or duration of drought[73,101,102] and drive aridification, a long-term shift toward a drier climate, which is a concern in already dry parts of the West.[76]

Between 1980 and 2022, drought and related heatwaves in the US caused $334.8 billion (in 2023 dollars as of July 2023) in damages; only tropical cyclones and severe storms were more costly (KM 22.1).[2] Droughts often reduce agricultural productivity and strain water systems,[103,104] driving shortages in water supplies and threatening power generation (KM 5.1).[105] River and lake transportation is also at risk due to drought (KM 24.4).

Drought stresses terrestrial and aquatic ecosystems[106] by leading to increased water temperature and salinity, reduced nutrients, lower oxygen levels, concentrated contaminants (Figure 4.2), loss of surface and groundwater connections, and declining productivity.[107,108] In addition, drought can exacerbate other disturbances such as pests and wildfire.[109] Ecosystems can be resilient under normal climate variability, but recovery after drought in a changed climate may not be possible, leading to the loss of ecosystem services and loss or migration of native and invasive species (Figure 8.6).[110,111]

Groundwater quality is also threatened by heat and drought. Warmer soil and groundwater temperatures can lead to decreased oxygen saturation, lower pH, and enhanced mineral weathering, all of which reduce water quality,[112] and coastal and island aquifers are at risk of seawater intrusion, rendering groundwater unpotable and potentially harming infrastructure (Figure 4.2; KMs 9.2, 21.2, 23.3, 28.2, 30.1).

Drought conditions have historically resulted in increased groundwater pumping in some regions of the US, a practice projected to increase with climate change.[55,56,113] Declining groundwater levels due to pumping can reduce streamflow (Figure 4.13)[48] and result in land subsidence.[114]

San Pedro River, Arizona



The San Pedro River in Arizona has been depleted by groundwater pumping, drying up wetlands and wildlife habitat.

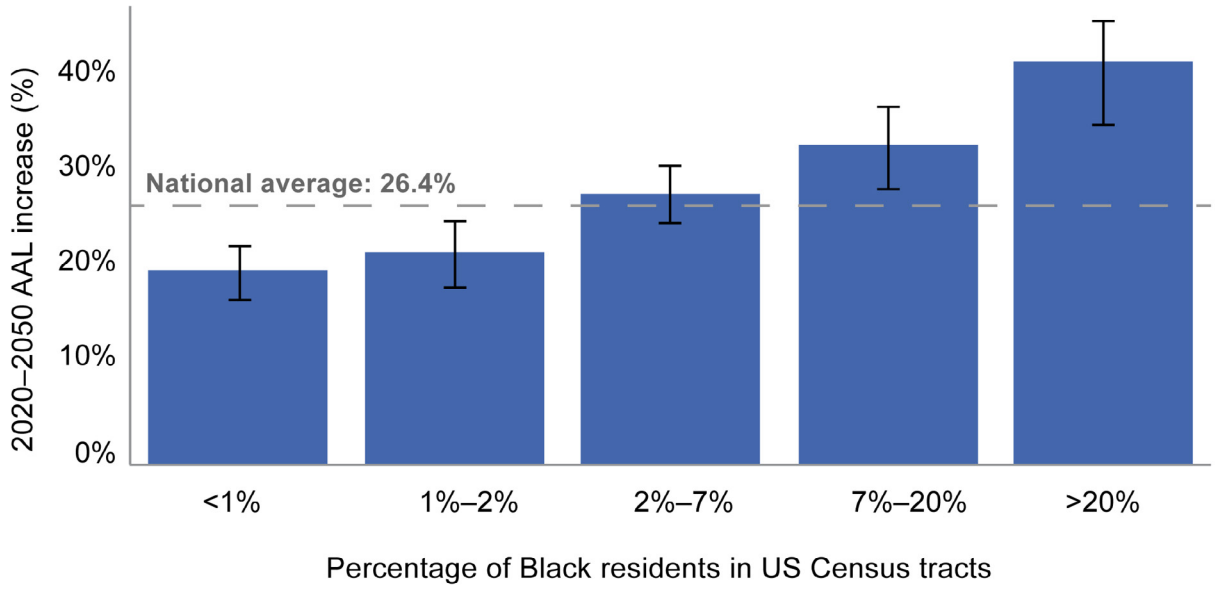
Figure 4.13. Groundwater pumping can reduce surface water supplies. One example is the San Pedro River in Arizona, where pumping that began in the 1940s has deprived wetlands and wildlife habitat of fresh water.[115] Photo credit: CochiseVista/iStock via Getty Images.

Disproportionate Impacts

Climate change creates unequal burdens on people and communities.[116,117,118] People who live along coasts and rivers or who work in agriculture and fisheries have increased exposure to water-related hazards.[119,120,121] Older adults, children, and residents of low-income neighborhoods and rural areas are at greatest risk of exposure to pathogens and pollutants from climate change–driven impacts to water quality.[122,123,124]

Many Tribal and Indigenous communities reside in areas subject to coastal and riverine flooding and risk displacement from lands with cultural significance.[125,126,127] Neighborhoods that are home to racial minorities and people with low incomes have the highest inland flood exposures in the South.[128] Hispanic residents are 50% more likely to live in the 500-year floodplain,[129] while Black communities are projected to bear a disproportionate share of future flood damages (Figure 4.14; Box 4.2).[130] Drought can also have unequal impacts depending on economic sector, access to water resources, ability to irrigate, reliance on electricity, and socioeconomic status.[131]

Projected Increases in Average Annual Losses (AALs) from Floods by 2050



Losses due to floods are projected to increase disproportionately in US Census tracts with higher percentages of Black residents.

Figure 4.14. Average annual losses—economic damages in a typical year—due to floods in census tracts with a Black population of at least 20% are projected to increase at roughly twice the rate of that in tracts where Black residents make up less than 1% of the population. Black bars represent 95% confidence intervals. Adapted from Wing et al. 2022[130] [CC BY 4.0].

Box 4.2. Climate Change, Urban Flooding, and Inequality

Hurricane Harvey dropped record-breaking rainfall onto the Houston and Beaumont–Port Arthur metropolitan areas in August 2017 (Figure 4.15). The flooding, exacerbated by extensive urbanization, killed more than 100 people and caused an estimated $147.6 billion in damages (in 2022 dollars).[132] Harvey's rainfall was estimated to be about 15% to 20% heavier than it would have been without human-caused warming,[133,134,135] which increased the flooded area in the Greater Houston area by 14%,[136] leading to 32% more homes being flooded.[137] Many of the flooded properties were located outside FEMA's designated 100-year floodplains and not covered by federal flood insurance. Such properties were disproportionately inhabited by Black and Hispanic residents.[138] People with disabilities and residents of subsidized housing were also disproportionately affected.[139,140] Climate change's impact on flooding is expected to worsen these types of inequalities.

Residential Flooding from Hurricane Harvey

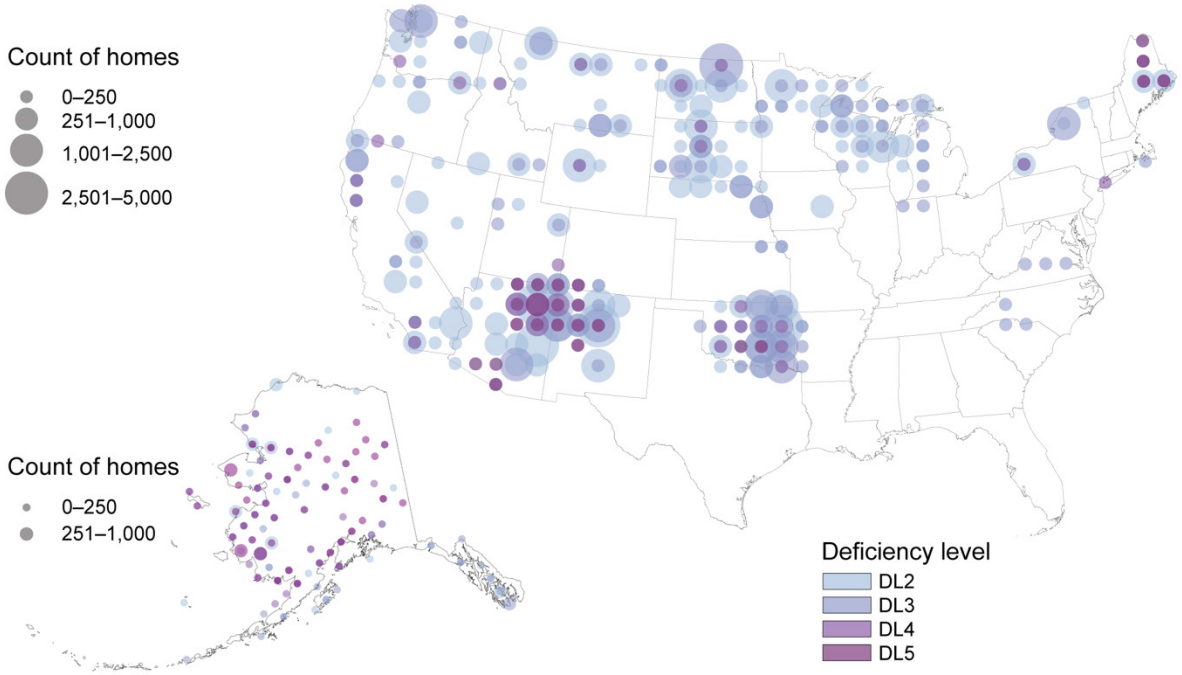


Flooding from Hurricane Harvey inundated residential neighborhoods in Port Arthur, Texas.

Figure 4.15. Photo credit: Staff Sgt. Daniel J. Martinez, US Air National Guard.

Across the Nation, drinking water delivery infrastructure is aging and deteriorating (KM 12.2), increasing the risks of contamination and delivery of unpotable water.[141] More than 1,000 community water systems—primarily serving older adults and people who are economically disadvantaged, rural, Indigenous, or with less education[142]—are already providing poor-quality water and are not prepared to cope with climate change-driven flooding, drought, and waterborne diseases (Figure 4.2; KMs 15.1, 15.2). For some Tribal and Indigenous communities, water infrastructure deficiencies threaten their social, physical, and mental well-being and impair their ability to thrive (KM 16.1).[143,144,145] Figure 4.16 shows the distribution and severity of sanitation facility deficiencies in American Indian and Alaska Native homes.[146]

American Indian and Alaska Native Homes Requiring Water and Sewer System Improvements



Water infrastructure supporting Tribal and Indigenous Peoples is particularly ill-equipped to handle increases in flooding and drought.

Figure 4.16. The Indian Health Service (IHS) maintains a database of American Indian and Alaska Native (AI/AN) homes requiring sanitation facility improvements within IHS service areas. The figure shows sanitation deficiency levels in AI/AN homes across the country ranging from level 2 (capital improvements are necessary to meet domestic sanitation needs) to level 5 (lacks a safe water supply and a sewage disposal system). The IHS does not collect data for Hawai'i, the US-Affiliated Pacific Islands, or the US Caribbean, but elevated rates of plumbing deficiencies are documented in those regions.[142] Figure credit: Indian Health Service.

Key Message 4.3

Progress Toward Adaptation Has Been Uneven

The ability of water managers to adapt to changes has improved with better data, advances in decision-making, and steps toward cooperation. However, infrastructure standards and water allocation institutions have been slow to adapt to a changing climate (*high confidence*), and efforts are confounded by wet and dry cycles driven by natural climate variability (*very likely, high confidence*). Frontline, Tribal, and Indigenous communities are heavily impacted but lack resources to adapt effectively, and they are not fully represented in decision-making (*high confidence*).

Approaches to Management and Planning

Uncertainty from natural variability has always been part of water resources planning, but as climate change affects different components of the water cycle, uncertainties around extreme events and water availability have increased. Responses to these growing uncertainties include climate adaptation and hazard mitigation through watershed management (KMs 6.1, 6.2);[147] nature-based solutions (KM 8.3); planned relocation;[148,149] floodplain management;[150] water conservation and reuse;[151,152] decision science;[153,154] reservoir optimization and artificial intelligence applications;[155,156,157] improved weather and streamflow forecasts;[158] municipal planning;[159,160,161] adaptive management systems;[162] stakeholder–scientist partnerships;[163] and adaptation guidance (KM 31.4).[164,165,166,167]

Adaptation Constraints

Climate change is overtaking water resources policymaking,[168,169] making risk reduction a continual exercise in catching up. For example, current rates of precipitation change outpace the regulatory changes needed to cope with them. Key rainfall metrics for design and decision-making are widely outdated;[170,171] updating these metrics is essential to protecting communities. While there have been recent advances in data collection, statistical methods, climate modeling, and weather forecasting, progress is difficult, in part because regulations, codes, and standards involve competing interests and often span multiple jurisdictions.[172,173,174]

Conflict, Competition, and Collaboration

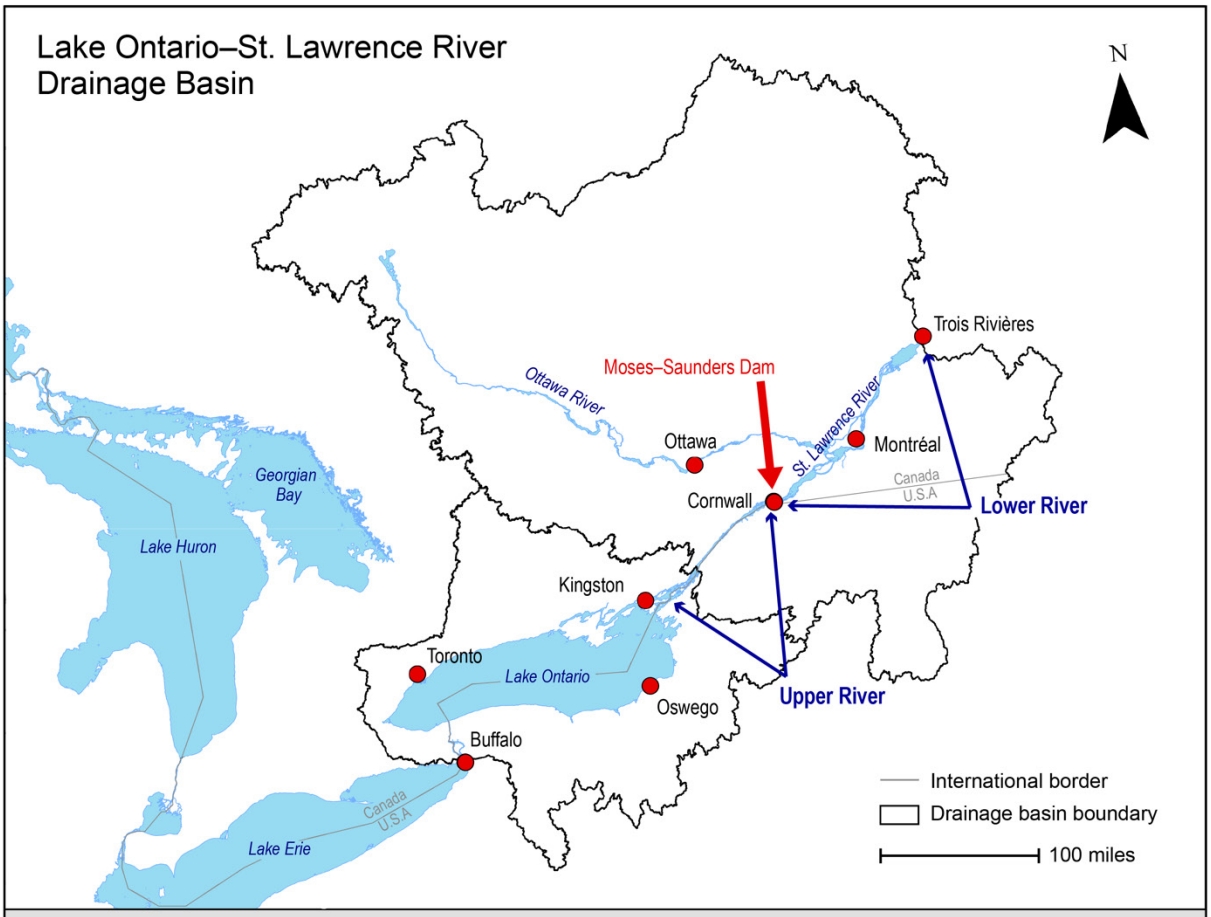
Climate change impacts to water supplies can result in competition, collaboration, or conflict. Frequently, water disputes in the western US are resolved through litigation.[175,176] However, under current severe drought conditions and in the context of existing legal frameworks, water interests in the Colorado River basin, including Mexico, are struggling to avoid litigation through negotiated settlements and voluntary use reduction (Box 28.1).[177,178,179] Some of these efforts now include Tribes and other water users who have traditionally been excluded from participation in negotiations, although representation remains uneven.[180]

In areas where flood risk is increasing, collaboration on flood hazard management at regional scales has become more urgent, as cooperation can provide solutions that are not available at the local scale (Box 4.3). This is especially true in the Midwest, where flooding is often regional and local solutions can push flood risks downstream.[181]

Box 4.3. International Cooperation in the Great Lakes

The Great Lakes, which contain the largest quantity of surface fresh water on Earth, are shared by two Canadian provinces, eight US states, and many sovereign Tribes and First Nations. Although ripe for conflict and competition, the waters have been equitably shared since the 1909 Boundary Waters Treaty.[182] In 2017, a management plan regulating Lake Ontario's levels and outflows was implemented (Figure 4.17).[183] It was the culmination of more than 16 years of scientific study, public engagement, and governmental review, including a collaboratively built model of the physical, environmental, and economic responses of the system to management and climate alternatives. Performance indicators yielded insights and quantified trade-offs, leading to a plan that balances flooding along the lake's New York and Ontario shorelines against flooding downstream on the St. Lawrence River at Montreal, Quebec. The plan also aims to restore the health and diversity of coastal wetlands and protect against extreme high and low water levels. An adaptive management committee evaluates the plan's performance under climate change and recommends adjustments.

Resolving Water Conflicts within the Lake Ontario–St. Lawrence River System



Plan 2014 determines outflows to the St. Lawrence River at Cornwall/Massena. Competing regions include Lake Ontario, Upper River, and Lower River. Interests include coastal flooding, erosion, shore protection, commercial navigation, hydropower, recreational boating, municipal and industrial water intakes, and ecological performance.

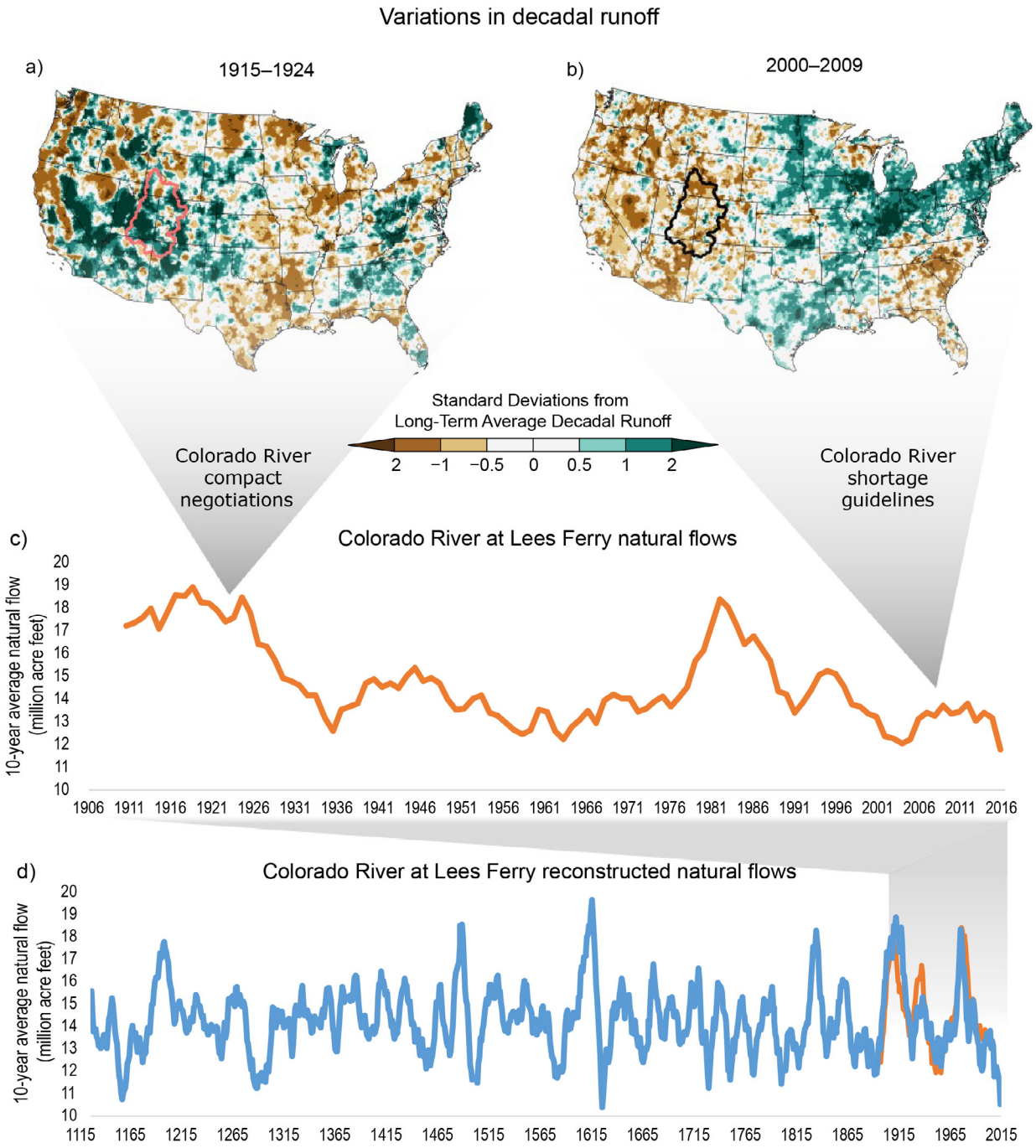
Plan 2014 was developed to manage Lake Ontario–St Lawrence River water levels, restore ecosystems, and account for climate change.

Figure 4.17. The map shows the geographic setting for an international plan between the US and Canada to cooperatively manage Lake Ontario. The plan balances interests upstream of the Moses-Saunders Dam with downstream interests. The collaborative framework used to develop the plan serves as a model of a successful approach to resolving water conflicts. Adapted from International Joint Commission 2014.[183]

The Effect of Natural Variability on Policy

Historical records and paleoecological evidence, such as tree ring data, show that natural variability in the climate system has resulted in multidecadal wet and dry spells in the past. [99] Climate projections indicate this pattern will continue, challenging planning and policy formulation for adaptation to climate change, and suggesting that durable and realistic long-term perspectives are necessary for robust policy development. For example, natural variability brought the wettest period in the past 1,200 years to the Colorado River in the early 20th century (Figure 4.18). The Colorado River Compact, negotiated in that period of relative abundance, allocated far more water than the river has since provided.[184] In the last years of the 20th century, sustained high reservoir levels prompted the development of guidelines for surplus allocation, but by the time those guidelines had been finalized, the current 22year drought had begun.[73] That drought has triggered unprecedented water use restrictions and is leading to more realistic policy discussions (Box 28.1).[177] Similar variability is present in climate and hydrology projections through the end of this century. The amplitude of projected 30-year-average wet and dry spells on the Colorado River may be twice the average projected decrease in streamflow by the end of this century;[185] as a result, multidecadal natural variability almost certainly will again lead to prolonged wet periods,[186] though diminished by higher temperatures.

Natural Hydrologic Variability Influences Policy



Natural hydrologic variability can promote urgency or complacency in long-term planning.

Figure 4.18. The figure shows hydrologic variability in both space and time: (**a**, **b**) runoff variability (a surrogate for streamflow variability) across the country between two decades, with the boundary of the Upper Colorado River Basin shown; and streamflow variability across time with (**c**) estimates of Colorado River flows from historical observations and (**d**) reconstructed flows from ancient tree rings (blue line), with data from (c) shown in orange. Wedges point to two negotiated policy events. Figure credit: Lynker and University of Colorado Boulder.

Adaptation Challenges Faced by Tribal and Indigenous Communities

To address water-related climate impacts, Tribes have voiced the need for climate impact assessments as a first step to resilience planning and identified information about climate change impacts to water as a top priority.[187] Many Indigenous communities lack data on water quality despite disproportionately experiencing water quality deficiencies.[188] Other data types critical to Tribal water management decisions are streamflow, temperature, precipitation, snowpack, and soil moisture, but these are not always available through federal information sources.[187]

Food security, protection of Traditional Knowledge, and Tribal capacity to implement adaptation plans, monitor and collect data, and conduct climate vulnerability assessments are also high priorities. Federally Recognized Tribes are eligible for federal assistance with climate change adaptation, but they face hurdles accessing these limited resources, including agency requirements (e.g., funding matches), lack of Tribal capacity, and navigating interagency processes.

Progress and Gaps in the Quality and Usability of Information

Water resources planning continues to be informed by past hydrologic records that do not reflect the impacts of climate change. Although some federal, state, and larger local agencies do use climate projections in planning, projections of precipitation, streamflow, water use,[189] and extreme events at the scale of local watersheds are rarely available, particularly outside of the contiguous US. Using projections is also costly because tools and techniques are specialized and not standardized. Finally, climate models project a wide range of uncertainty (Figure 4.3), requiring planners to use their best judgment about how to apply the information.

Data are foundational to adaptation. State and federal agencies have been collecting valuable climate, hydrology, and water use data for over a century, but these data are sparse in lightly populated and lower-income areas.[185] Increasingly, modeling and remote-sensing data are filling the gaps. High-resolution elevation and environmental data collected from airborne and spaceborne platforms provide detailed topographical and hydrological information that can be used to map flood hazards and snowpack[190,191] and refine real-time snow simulation.[192,193] Evapotranspiration is being estimated using satellite remote sensing combined with vegetation models,[194] providing early warning of emerging droughts,[195] and satellites are now being used to detect groundwater depletion.[196] Nevertheless, expanding direct observational data collection is still key to tracking environmental conditions and supporting development and testing of remotely sensed data and models.

Traceable Accounts

Process Description

With support from the chapter point of contact and the federal coordinating lead author, the chapter lead author selected authors for their expertise in assessing climate impacts to the Nation's surface and groundwater resources and the consequences of those impacts to human and natural systems, with an emphasis on the authors' ability to bring diverse perspectives to the team. The team comprises experts drawn from several regions across the country who work under various employment types (i.e., private business, academic institutions, and local, state, and federal governments), come from diverse backgrounds, and represent a range of combinations of age and gender. The team met virtually multiple times to scope the chapter, with each author offering their own priorities about what a chapter about the Nation's water resources should cover, taking into consideration the goals of this Assessment, the topics covered in previous National Climate Assessments (NCAs), and the topics of the other 31 chapters in the NCA5. The team's discussions revolved around these questions: How are changes in climate influencing water input volume and movement? How are extremes and the notion of extremes changing? How are changes in climate stressing both natural and human-made systems? What are the environmental justice considerations and the distribution of impacts? Are current climate data and tools adequate for decision-makers? And what are the interconnected climate risks? With these questions in mind, the team iteratively developed a draft outline for the chapter. That outline was made available online for public review and comment. The team presented and participated in a virtual, public, four-hour workshop and discussion, collecting comments and suggestions for the chapter from workshop participants. Workshop comments and formally submitted comments were taken into consideration in development of the chapter text. The Third Order Draft was presented to the public by five of the authors in a webinar hosted by Western Water Assessment at the University of Colorado. The author team met virtually at least twice per month during periods when the draft was not out for review. The team also met in person at the NCA5 All-Author Meeting held in April 2023 in Washington, DC. The meetings were used to set interim deadlines, assess the status of tasks, discuss language choices, find consensus on Key Messages and figures, develop responses to comments on drafts, and support each other with references and text reviews.

Key Message 4.1

Climate Change Will Continue to Cause Profound Changes in the Water Cycle

Description of Evidence Base

The hydrologic component maps shown in Figures 4.3, 4.5, 4.6, 4.7, and 4.9 constitute part of the evidence base. They show mid-21st-century projections of water cycle components based on an intermediate scenario (RCP4.5). Projections of water cycle components are available for both RCP4.5 and RCP8.5 scenarios, but both scenarios show similar hydrologic responses at midcentury, neither are available as 100-year projections, and space in this chapter is limited; as a result, only RCP4.5 projections are presented here. The central map of the contiguous US (CONUS) in each of these figures represents the average of all 32 Coupled Model Intercomparison Project Phase 5 (CMIP5) projections chosen for this discussion.[197] The Alaska and Hawai'i maps represent the average of 10 CMIP5 projections. The wettest and driest 20% of projections show the range of outcomes from the 32-projection set for CONUS, illustrating the uncertainty surrounding water cycle responses to climate change. Outside CONUS, downscaled climate projections are limited, especially those needed to map projected changes in hydrologic components for the US Caribbean and US-Affiliated Pacific Islands. The absence of projections for actual evapotranspiration, soil moisture, and

runoff contribute to uncertainty when assessing future water security challenges for these regions. Further information about the data used to generate the maps can be found in the figure metadata.

Because the focus of this chapter is terrestrial fresh water, the authors relied heavily on Chapter 2 (Climate Trends) and Chapter 3 (Earth System Processes) for their assessments of precipitation trends and projections, particularly extreme precipitation trends and projections.

Regarding evapotranspiration, there is general consensus that warming temperatures will enhance evaporative demand (potential evapotranspiration, PET) across the Nation (Ch. 3);[43,44,75] however, uncertainties in vegetation response to warming reduce confidence in evapotranspiration (ET) projections.[75] In many parts of the country, projected changes in annual evapotranspiration by the end of this century are not robust, and there is disagreement among models across the southern states and parts of the central US.[43] The degree and sometimes direction of observed changes in PET and ET are also less certain, particularly east of the Rocky Mountains, due to differences in the trends of the variables that force PET.[12] Nor are these trends well supported by direct observation. There is a lack of information on more recent trends in pan evaporation across the US. Pan evaporation is a useful concept to estimate atmospheric evaporative demand but it is strongly affected by local environmental conditions, which can drive contradictory trends in pan evaporation across a broader region,[198] as is observed across the US.[199] For example, increases in local humidity (e.g., from irrigation) or land-use changes (e.g., changes in tree density near the pans) could affect evaporation from the pans. Therefore, pan evaporation may not provide a reliable indication of regional-scale trends in evaporative demand. The disagreement among observational data and reanalyses limits our confidence in past ET and PET trends. Complexities related to vegetation, as well as the competing effects of multiple evaporation drivers, make assigning nationally consistent likelihood and confidence challenging. However, the balance of evidence suggests with *medium confidence* that evaporation is expected to increase in places where moisture is not a limiting factor to atmospheric demand.

There is widespread consensus that increases in temperature will decrease the proportion of US precipitation that falls as snow,[14,15,24,43] decrease snow extents,[24,25] advance the timing of snowmelt rates and pulses,[16,27] increase the prevalence of rain-on-snow events,[70,71] and influence how snow water resources are partitioned to runoff.[19,20]

Since parts of Alaska and the highest elevations in the contiguous US may be cold enough to sustain snowfall in future climates, some studies have projected increases in snow volume in these locations with future increases in precipitation. However, those increases in snow are expected to be vastly outweighed by the future decreases in snow elsewhere, particularly across the western US and by the late 21st century for all intermediate (RCP4.5 and SSP2-4.5) and higher scenarios.

It is well established that groundwater and surface water are connected resources and that groundwater can help stabilize surface water supplies.[47,48] Similarly, there is agreement that loss of shallow groundwater can exacerbate droughts and decrease streamflow. There is also agreement that warmer temperatures will increase water demand and that this could increase groundwater pumping.[52,53,54]

Major Uncertainties and Research Gaps

Uncertainties stem from future projections of climate. This may be particularly true for late-21st-century projections that are dependent on the degree to which societies will respond to climate change. The literature employs different projections and emissions scenarios, as well as metrics and measurements that vary in their degree of climate sensitivity, resulting in studies that are not always directly comparable.

Understanding recent and potential future flood responses to climate change is difficult for several reasons. Floods are the product of complex subseasonal to interannual interactions between rainfall, soil moisture, evapotranspiration, snowpack/melt, and other processes. Isolating climate change impacts on

inland flooding is further complicated by the hydrologic "replumbing" wrought by urbanization and dams. For these reasons, the translation of rainfall trends into flood changes is complex and poorly understood. National[65,200] and global[201] examination of historical flood records has concluded that climate influences have been relatively limited, contradicting an earlier study that argued that the largest floods have increased in severity.[202] This latter argument is further contradicted by evidence that floods in the central US have become more common but not more intense.[203,204]

However, major floods are by definition rare, making detection and attribution of changes difficult. Thus, a lack of statistically significant trends in observed floods does not necessarily indicate that such events are not changing. Indeed, a relatively limited number of geographically focused case studies have painted complex pictures of climate-related flood changes that are lacking in broader regional and national analyses. Additional place-based case studies—as opposed to regional- or national-scale analyses—could help unravel the complex interactions between climate and non-climate flood drivers.

Given the first-order influence of temperature and precipitation change on snowfall, there is high certainty that future US snow cover, snow volume, and snow persistence will change.[24] However, there is some disagreement in the literature about the extent and direction (positive or negative) of change in surface water availability with future changes in climate. Existing studies indicate both increases and decreases in future runoff for different US hydroclimatic regimes.

In particular, there is uncertainty in the degree to which temperature may impact flow in some major river systems in the West.[205,206] Significant disagreements in the direction of observed soil moisture trends remain,[38,39,40] largely because it can be challenging to estimate with remote sensing or models, and the existing in situ soil moisture–monitoring network is insufficient.[37] Uncertainties can also be introduced because not all products are directly comparable, capturing trends over slightly different depths, although modest differences are probably not a major source of error. There is also uncertainty in soil moisture projections related to model, season, and soil depth.[38,42,43]

Similarly, there is uncertainty in both the magnitude and direction of groundwater storage changes, primarily due to uncertainty in future groundwater management policy and uncertainty in future recharge. This is due to uncertainty in both the human response to changing climate conditions and research gaps in quantifying natural groundwater recharge. Groundwater pumping is controlled by a myriad of human factors such as population, water policy, crop choices, and irrigation technology. While it is well established that warmer temperatures can increase water demand,[52,53,54] and historical trends demonstrate unsustainable groundwater usage in the past (as discussed in NCA4), future groundwater pumping increases will depend on water management practices and policy. Groundwater recharge is similarly uncertain.[50,51] Projected increases in large precipitation and flooding events are expected to increase recharge (known as episodic recharge events). However, the quantity of this recharge is less certain and highly dependent on the nature and timing of the storms that occur. Also, while increases in recharge may be counteracted by changes in plant water usage and snowpack that can decrease natural recharge, the magnitude of these recharge changes has not been well quantified. Separating the impacts of groundwater pumping from climate trends is particularly challenging due to a lack of long-term groundwater monitoring wells, especially outside of the most heavily groundwater-developed areas.

Description of Confidence and Likelihood

The author team determined that the evidence points to *medium confidence* that there will continue to be increases in precipitation in Alaska and in the northern and eastern regions of the US and decreases in precipitation in the Caribbean and the Southwest. Despite lingering uncertainties around average precipitation, there is *very high confidence* from both observations and projections that extreme precipitation events are becoming more frequent nationwide, and that it is *very likely* this trend will continue in the

future. The disagreement among observational data and reanalyses limits our confidence in past ET and PET trends. Complexities related to vegetation, as well as the competing effects of multiple evaporation drivers, make assigning nationally consistent likelihood and confidence challenging. However, the balance of evidence suggests with *medium confidence* that evaporation will increase in places where moisture is not a limiting factor to atmospheric demand. Based on current trends and climate model projections, there is *high confidence* and it is *very likely* that warming temperatures will increase the demand for surface and groundwater for crops and human use. Given the direct influence of rising temperatures on snow, there is *high confidence* and it is *very likely* that the extent, volume, and duration of snow cover and melt upon which human and natural systems rely is and will continue to be reduced by warming.

Key Message 4.2

Water Cycle Changes Will Affect All Communities, with Disproportionate Impacts for Some

Description of Evidence Base

Observational records now span time periods long enough to evaluate changes in the volume, variability, and timing of water availability.[11] The magnitude of these changes, and their agreement with model projections, vary with hydroclimate regimes across the US.

While it has been difficult to establish clear linkages between increases in extreme precipitation and trends in "traditional" measures of flood activity such as peak streamflow rate, attribution studies have apportioned some of the historical increases in flood damage to precipitation change.[68,69] It is probable that many of these increases have been concentrated in urbanized watersheds, which are more sensitive to rainfall than rural and natural settings.[74] Flood vulnerability, including in urbanized areas, tends to be concentrated in historically marginalized and socioeconomically disadvantaged neighborhoods.[130] There is increasing consensus that systematically disadvantaged communities have been and will continue to be most impacted by these hazards, due to factors such as inadequate climate/hydrological monitoring, deferred infrastructure maintenance, and insufficient access to recovery resources.[207]

There is ample literature describing the impacts of floods, fires, and drought events on a wide variety of water quality hazards.[6] These studies provide insights into impacts to water quality hazards from intensified events due to climate change, and studies specific to climate change impacts on water quality are becoming more prevalent. There are some reports of specific benefits to contaminant concentrations from increased or decreased precipitation, but there is no consensus that water quality will improve with climate change.

There is widespread consensus that increases in air temperature will impact water quality by increasing water temperatures, resulting in less oxygen-rich water, exacerbating harmful algal blooms, increasing pathogens, and creating problems with drinking water taste and odor.[6,7]

Similarly, there is consensus that increased precipitation and intensity will degrade water quality due to urban storm water and combined sewer overflows, increased agricultural runoff, and riverine flooding. There is less certainty in regions of the country where precipitation is not increasing or decreasing. Compounding factors of increasing temperatures and aging stormwater and sewer systems and water reservoirs can exacerbate problems due to too much or too little water.

The literature is rife with observations of segments of the population being negatively affected by climate change, especially water-related hazards. There is consensus that these negative impacts of water-related climate change will be felt disproportionately among marginalized and low-income people.[122]

Major Uncertainties and Research Gaps

There is moderate uncertainty about the degree to which land-surface changes will drive nonstationary changes to the volume and timing of water resources. There is a lack of research on the linkages between climate change and flooding.[68] There is uncertainty about the extent to which traditional design storms—that is, storms of particular intensity and duration, used in floodplain and built environment planning—and flooding assumptions based on older observations reflect current and future flood conditions.[171] Additional research into the effects of climate change on water quality would improve our understanding of impacts, particularly in the face of compounding factors such as aging infrastructure, wildfires, and increased agricultural runoff.

Description of Confidence and Likelihood

There is strong evidence that climate change imparts a number of important shifts in local and regional hydrologic cycles, and that when combined with land-use changes and other human factors, increases are *likely* in the frequency, severity, duration, and damages from floods (*high confidence*) and drought impacts are increasing (*medium confidence*). There is a more limited body of work on the effects of climate change on water quality; thus there is *medium confidence* that climate change is degrading water quality. However, there is still uncertainty about how climate drivers may shape harmful algal blooms, a significant factor in water quality. Based on the vast literature documenting current, disparate impacts to frontline communities from floods, droughts, and the exposures they bring, there is *high confidence* and it is *very likely* that frontline communities will be at disproportionate risk from water-related hazards exacerbated by climate change.

Key Message 4.3

Progress Toward Adaptation Has Been Uneven

Description of Evidence Base

There are many examples of climate change overtaking the speed of adaptation,[168,169] including communities caught off guard by extreme precipitation and drought events amplified by climate change.[96,133] A wide array of literature over the past decade has identified the safety and economic risks posed by aging water systems and changing hydrology.[87] Since the publication of NCA4, expanded data collection, improved climate projections, and better short- to midterm forecasts support better water resource management and planning. However, local water resource managers are still struggling to find accessible, usable science and data at the appropriate spatial scale, and they continue to rely on historical records that often do not reflect current and future water availability and timing. Disaster management literature contains many examples of public complacency and/or urgency in preparing for extreme events.[208]

A growing literature focuses on providing scientific information that is more usable for water resource planning and management.[164] There has been less work in assessing success and evaluating how equitable these approaches have been.[209]

A number of retrospective reviews highlight the omission of frontline, Tribal, and Indigenous voices and benefits from water projects.[180] Long-standing legal entitlements, established before climate change was a consideration, are well documented. The bulk of senior water rights and legal entitlements in the West are held by Tribes and agricultural water users but governed by state and federal decrees, agreements, and compacts that were not written to be flexible or responsive to a changing climate. Current literature is documenting these barriers and assessing emerging approaches to work past them.[177]

Major Uncertainties and Research Gaps

Building climate resilience in hydrologic systems is challenging given the high uncertainty of climate variability and change. Gaps in actionable local-scale water data are particularly problematic, especially translating projections from global climate models to the regional and local level. System-level approaches and the use of resilience metrics are also areas ripe for improvement.

There is moderate uncertainty about the degree to which changes to land surface characteristics will drive changes to the volume and timing of water resources, and the degree to which existing infrastructure and historically defined allocations will be able to adapt. A large part of this uncertainty is related to how quickly human actions and policies react to hydrologic hazards.

Description of Confidence and Likelihood

Rising water-related disaster costs, communities ill-prepared for floods and droughts, and basin water users deferring difficult water allocation decisions are just a few of the pieces of evidence leading to *high confidence* that adaptation efforts are proceeding unevenly relative to the rate of climate change and that this is *very likely* (with *high confidence*) due in part to natural climate variability masking long-term changes. The history of water resources decision-making rarely includes participation by frontline, Tribal, or Indigenous individuals or communities. Their exclusion from negotiations, compacts, decrees, and other allocation actions supports an assessment of *high confidence* that frontline, Tribal, and Indigenous communities have not had full representation in water resources decision-making in the past, despite being affected by those decisions.

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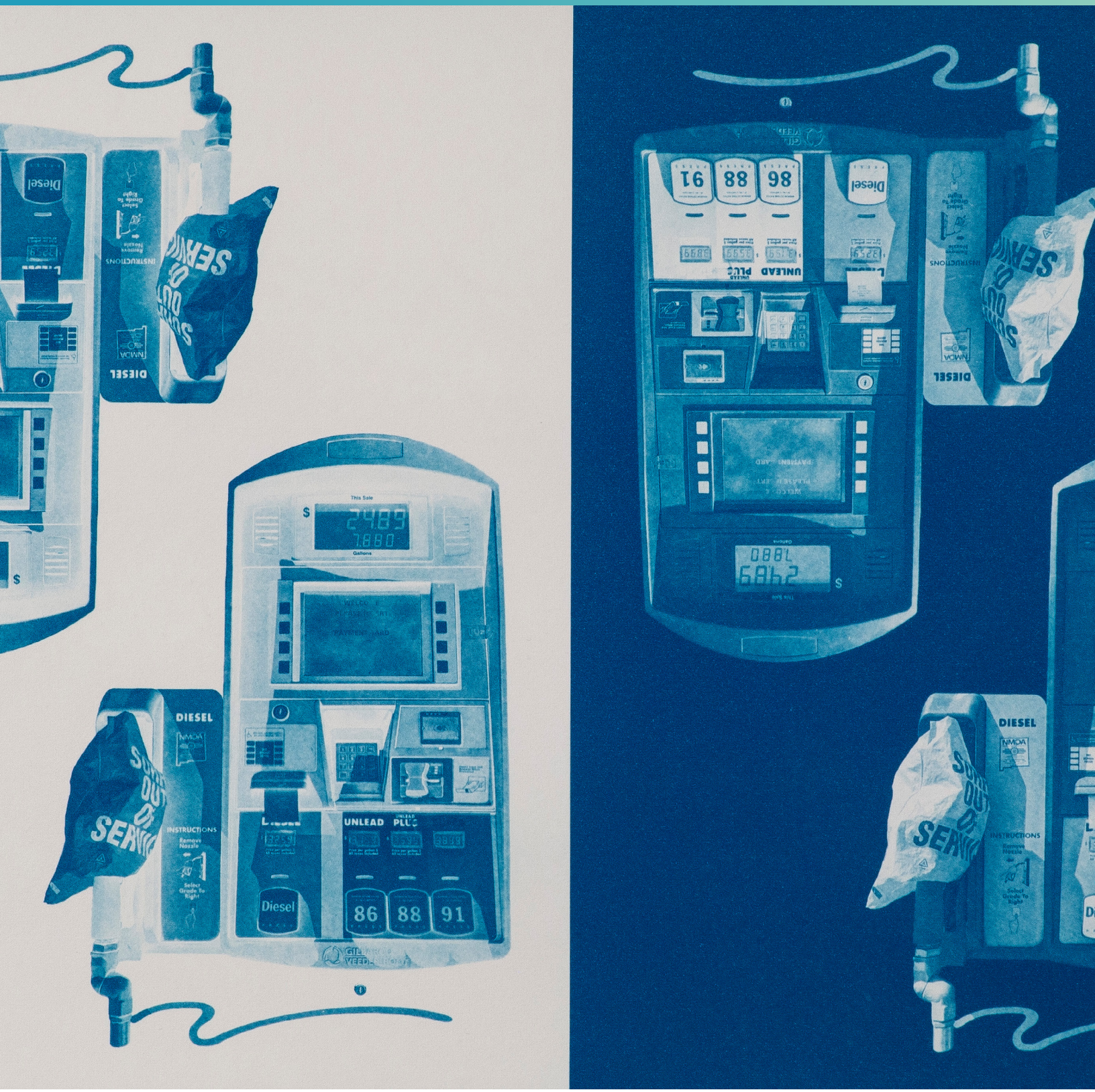
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Energy Supply, Delivery, and Demand



Chapter 5. Energy Supply, Delivery, and Demand

Authors and Contributors

Federal Coordinating Lead Author

Craig D. Zamuda, US Department of Energy

Chapter Lead Author

Craig D. Zamuda, US Department of Energy

Chapter Authors

Daniel E. Bilello, National Renewable Energy Laboratory
Jon Carmack, US Department of Energy
Xujing Jia Davis, US Department of Energy
Rebecca A. Efroymson, Oak Ridge National Laboratory
Kenneth M. Goff, Idaho National Laboratory
Tianzhen Hong, Lawrence Berkeley National Laboratory
Anhar Karimjee, US Department of Energy
Daniel H. Loughlin, US Environmental Protection Agency
Sara Upchurch, Federal Emergency Management Agency
Nathalie Voisin, Pacific Northwest National Laboratory

Technical Contributors

Laura West Fischer, Electric Power Research Institute
Zarrar Khan, Pacific Northwest National Laboratory

Review Editor

Ariel Miara, National Renewable Energy Laboratory

Cover Art

Maria Trunk

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Introduction

Reliable and affordable clean energy is important for quality of life, economic competitiveness, and national security. However, much of today's energy infrastructure was designed for the 20th century, making it vulnerable to climate impacts, including more frequent power and fuel interruptions, increased damages to energy infrastructure, increased energy demand and reduced supply, and cascading effects impacting other sectors, including transportation, communication, and health and safety.

Societal changes are altering vulnerabilities of energy systems and communities to climate change. Changing risks result from shifts in the energy generation mix that lower greenhouse gas (GHG) emissions; increased electrification of buildings and transportation; technological innovation creating new demands for energy; greater susceptibility of energy components to domestic and international supply chain disruptions; and an increasingly automated, interconnected system susceptible to physical and cyberattacks.

While atmospheric GHG concentrations continue growing at historically high rates due to factors such as increased global energy use, energy system decarbonization is reducing the rate of GHG emissions.[1] Demand for energy is increasing, outpacing energy efficiency improvements, and electrification is expected to grow.[2,3] Adaptation to environmental change, along with improved resilience of energy production and delivery systems to climate-related events, is underway. Energy system innovations include reductions in technology costs and operational and performance improvements for energy production, delivery, and storage; distributed generation and microgrids; demand-side management; zero-emissions buildings and vehicles; and energy-market design and governance structures.

Evolving policy focuses on a transition to net-zero energy systems and away from fossil fuels. The Bipartisan Infrastructure Law[4] and the Inflation Reduction Act (IRA)[5] are the largest investments in climate and energy in American history (Chs. 25, 32).[6,7,8] These laws prioritize investments for overburdened communities and advance the Justice40 Initiative, which commits to delivering benefits of climate, clean energy, and related federal investments to these communities.[9] State and local actions include building codes, incentives, and bans intended to encourage a shift to clean energy sources.[10,11] Progress is underway, but further actions are needed to increase the pace, scale, and scope of the energy transition to deliver more clean energy and build a more resilient energy future.

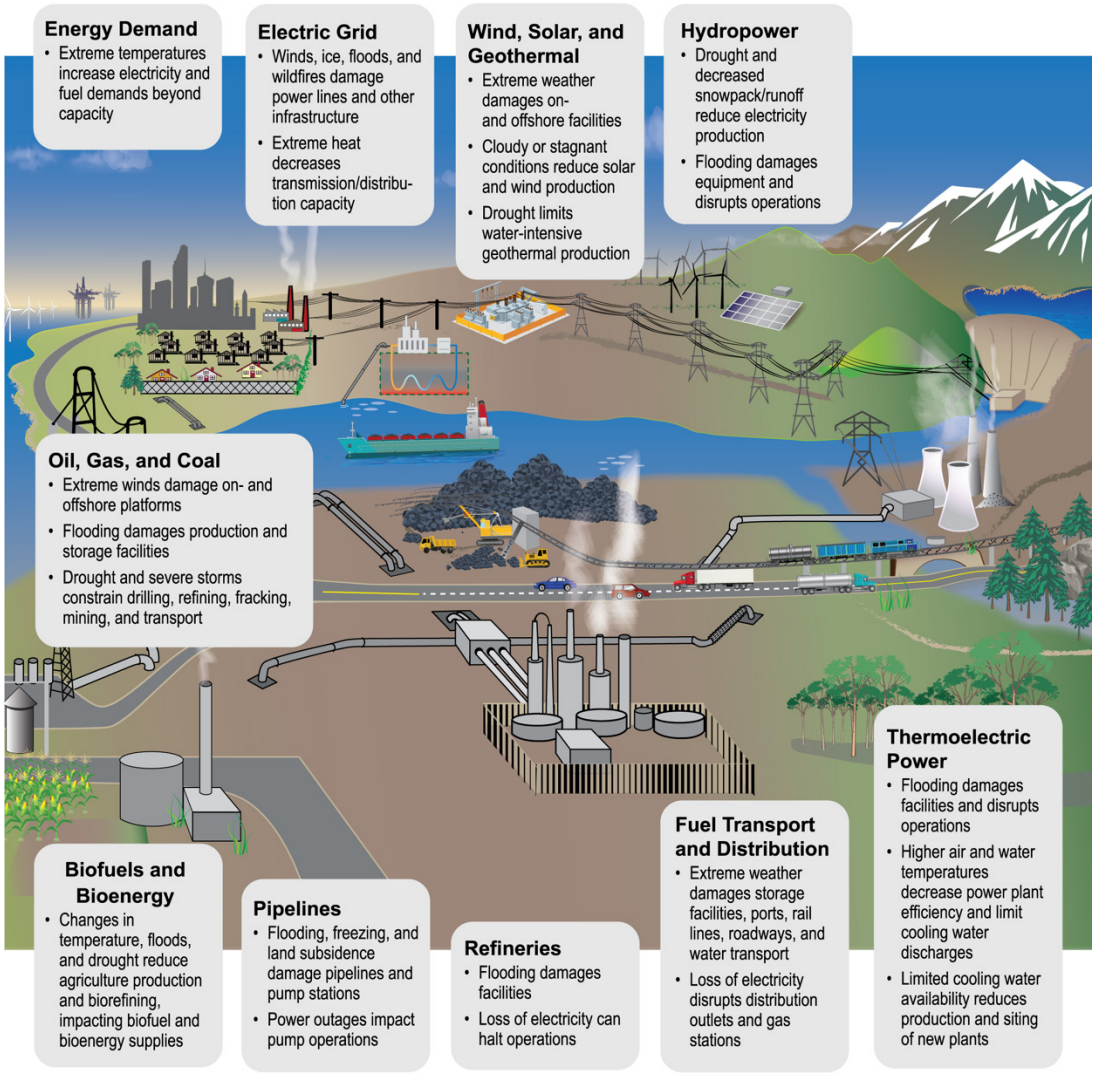
Key Message 5.1

Climate Change Threatens Energy Systems

Energy supply and delivery are at risk from climate-driven changes, which are also shifting demand (*virtually certain*, *very high confidence*). Climate change threats, including increases in extreme precipitation, extreme temperatures, sea level rise, and more intense storms, droughts, and wildfires, are damaging infrastructure and operations and affecting human lives and livelihoods (*virtually certain*, *very high confidence*). Impacts will vary over time and location (*virtually certain*, *very high confidence*). Without mitigation and adaptation, projected increases in the frequency, intensity, duration, and variability of extreme events will amplify effects on energy systems (*virtually certain*, *very high confidence*).

Climate change affects all aspects of the energy system—supply, delivery, and demand (Figure 5.1)—through the increased frequency, intensity, and duration of extreme events and through changing climate trends (Ch. 2). Energy production and distribution are vulnerable to flooding, hurricanes, drought, wildfires, and permafrost thaw. Extreme temperatures increase energy demands and stress electricity operations, leading to outages that disrupt societal services. The magnitudes of climate threats vary temporally and spatially (e.g., droughts and wildfires in the Southwest, hurricanes and storm surge on the Gulf and East Coasts).

Climate Change Impacts on the Energy System



All aspects of the US energy system are vulnerable to the effects of climate change.

Figure 5.1. Climate change impacts all components of the Nation's energy system—resource extraction and processing, energy transport and storage, electricity generation, and energy end use. Adapted from DOE 2013.[12]

Energy Supply

Generation Systems

Sea-level rise, hurricane-force winds, and inland flooding impact coastal energy infrastructure and strategic national assets,[13,14] including the Nation's Strategic Petroleum Reserve.[15] The Gulf of Mexico region accounts for a significant portion of the Nation's crude oil production, petroleum refining, and natural gas processing capacity.[16] Coastal energy supply is especially affected by climate change and can disproportionately impact isolated and overburdened communities.[17,18]

Storm events, extreme temperature, droughts, and wildfires damage inland energy generation systems and impact operations.[19,20] Solar and wind energy generation is affected by heat, smoke, soot, and hail.[21,22,23] Flooding and freezing of extraction, storage, and distribution equipment impact natural gas production and power generation and cause power outages.[24] Extreme heat reduces the capacity and efficiency of natural gas and steam turbines.[25,26] More intense hurricanes have increased disruptions to nuclear power.[27] Drought and extreme weather can limit biofuel feedstock supplies.[28] Renewable energy will be affected by changes in wind and solar resources, although the magnitudes and locations of these effects are uncertain.[29,30,31,32,33,34] Uncertainty regarding climate impacts on wind and solar resources remains, but downscaled climate model data coupled with energy sector models are advancing.

Electricity Generation and Water Availability

Water is used in electricity generation, including in producing hydropower and hydrogen, cooling thermoelectric generators, maintaining solar photovoltaic (PV) installations,[35] and producing feedstocks for bioenergy. Water-dependent generation is stressed by droughts,[36,37,38] snowpack depletion,[37] increases in stream temperature,[39] reservoir evaporation,[40] dam removal to restore rivers and their societal and ecological roles,[41] increasing demands for other water uses, and pumping limits that increase cost.[42]

Most of the western United States is experiencing a megadrought, disrupting water supply and hydropower generation (Ch. 2).[37,43,44] Increasing energy demand due to higher summer temperatures, coupled with a projected decrease in summer hydropower generation, will magnify the potential for energy shortfalls.[45,46]

Thermoelectric generators provide most of the Nation's electricity and rely on significant volumes of water.[47,48,49] Deployment of some low-carbon technologies, such as carbon capture, utilization, and storage (CCUS), increases this water dependence.[50] New cooling technologies for small modular reactors provide options for addressing water availability constraints.[51] The compounded impacts of decreasing summer river flows, increasing temperatures, and, in many regions, temperature limits on discharge water reduce the efficiency and generation capacity of thermoelectric generators,[52] decreasing reliability during extreme conditions.[39,53,54] Operations relying on reservoir storage for cooling water face increasing vulnerability from storage levels dropping below critical thresholds, particularly in the Southwest.[55]

Energy Delivery

Electricity Delivery

Power outages from extreme weather are increasing across the US. The average number of major power outages (exceeding 50,000 customers) increased by roughly 64% during 2011–2021, as compared to 2000–2010, with the most weather-related power outages attributed to extreme cold (22%), tropical cyclones (15%), and severe weather (58%).[56] Annual expenditures on electricity transmission and distribution infrastructure could rise up to 25% by 2090 under a very high scenario (RCP8.5) compared to a scenario without climate change.[57] Additional costs for power interruptions could reach $4.7 to $8.3 billion per year by 2090 (in 2022 dollars).[57]

Extreme heat events are increasing in frequency and duration (KM 2.2).[58,59] High temperatures increase powerline sagging and reduce the efficiency of transmission and distribution, stressing the grid during periods of increased demand.[57,60] Electricity infrastructure, including transformers and transmission lines, deteriorate faster in extreme temperatures, and cables have reduced carrying capacity with rising air temperature.[25,57]

Wildfires and extreme weather events pose challenges to electricity infrastructure.[61,62,63,64] Aboveground powerlines are susceptible to damage from high winds and falling vegetation.[65,66] Powerlines are also susceptible to damage and reduced efficiency from ice[67] and wildfires, including soot.[57,63,68] Flood scours, subsidence, and landslides, which increase with drought and increased groundwater pumping,[69] are damaging buried powerlines and natural gas pipelines. Coastal power substations are at risk from storm surges exacerbated by sea level rise.[70,71]

Examples of extreme-events impacts on electricity delivery include substantial damage to Puerto Rico's transmission and distribution lines after Hurricane Maria;[72] hotter and drier conditions in the Southwest enabling stronger and longer-lasting wildfires,[19] threatening the wildland–urban interface;[20] and risk of wildfires influencing utility-initiated power shutdowns in California during periods of high winds and dry conditions.[20,73,74]

Oil and Gas Delivery

Climate change and extreme weather disrupt oil and gas supply chains.[75,76,77,78] Hurricanes, flooding, and sea level rise threaten onshore and offshore infrastructure and operations.[79] These threats would become more intense in a warming world (Ch. 2). Disruption of petroleum supplies has broader impacts on transportation, buildings, and industrial products.[80]

In 2020, Hurricane Laura disrupted more Gulf of Mexico crude oil production than any other storm since 2008.[81] Onshore processing facilities and power supplies were damaged, and industry response was limited by lack of resources, personnel, processing facilities, and power. Flooding from Hurricane Harvey in 2017 damaged large pipelines,[82] and excessive precipitation damaged floating-roof storage tanks.[83] Hurricane Ida in 2021 disrupted up to 95% of the Gulf Coast's crude oil and gas production.[84]

Extreme cold events in areas inexperienced with such temperatures are impacting oil and gas equipment and operations.[24] In regions where natural gas is used for heating and power generation, cold events are challenging because of increased demand combined with the risk of infrastructure failure.[85,86]

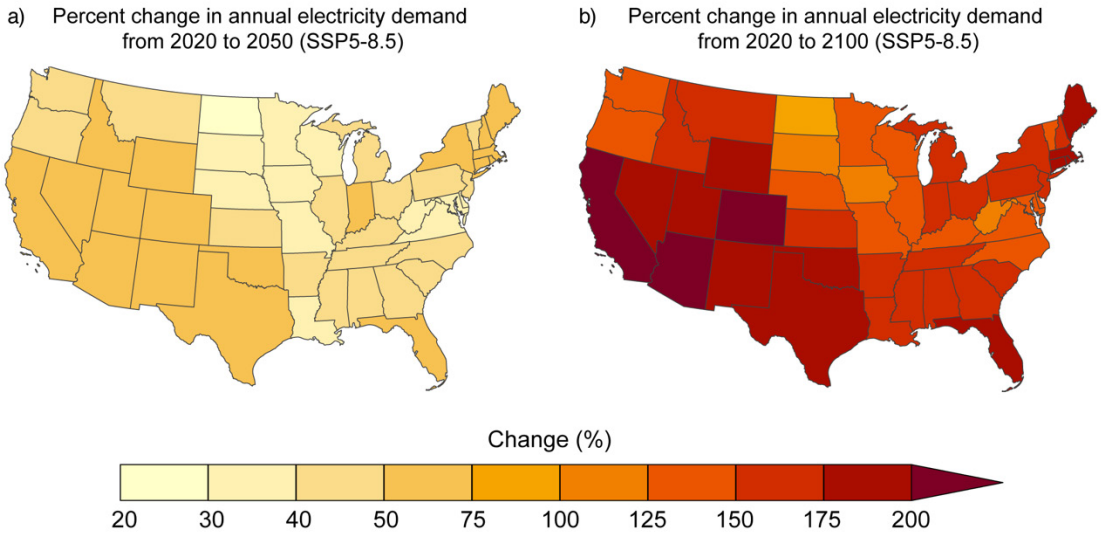
Although climate change often increases risks to energy production and delivery, warming temperatures have mixed effects on oil and gas production in cold regions. Warming benefits offshore production and shipping of petroleum products off the Alaska coast by decreasing sea ice and opening shipping routes. Average annual Arctic sea-ice extent during 2011–2020 reached its lowest level since at least 1850 (Ch. 2).[87] Ice-free summers are projected by 2050.[87,88] Warming temperatures in Alaska endanger inland oil and gas production and delivery as permafrost thawing compromises the structural integrity of wells, pipelines, storage tanks, railroads, and roads, impacting consumers and potentially contributing to methane leakage.[89] Fewer days for road travel on decreasing frozen tundra also has an impact on oil and gas exploration and production.[90,91]

Energy Demand

Energy demand is projected to increase through 2050, driven by warming temperatures, increasing electrification, and economic growth.[3,92] Despite the increase, overall intensity of energy demand (energy consumed per household or per square foot of commercial floorspace) is expected to decrease.[3,92] Energy system modeling projects decreases in overall energy use relative to current levels if net-zero CO_2 emissions are achieved (KM 32.2).

Electricity demand is growing in many regions of the US, driven by population and economic growth; increased adoption of electric vehicles, heat pumps, and water heaters; and decarbonization goals, spurring additional electrification of transportation, industry, and buildings.[93] These trends also alter peak demand patterns.[94,95,96] Increased temperatures can further increase overall electricity demand, as illustrated in Figure 5.2.[97,98]

Projected Changes in Electricity Demand



Due to climate change, electricity demand is projected to increase over this century.

Figure 5.2. Global change intersectoral modeling forecasts[97] that do not reflect the provisions of the Inflation Reduction Act project a potential increase in annual electricity demand of 25% to 70% from 2020 to 2050 (a) and 96% to over 215% from 2020 to 2100 (b) across much of the country, driven in part by increased ambient temperatures. Alaska, Hawai□i and US-Affiliated Pacific Islands, and the US Caribbean are not included due to the lack of high-resolution climate data informing those projections, but similar trends are expected. Increasing electricity demand is expected based on socioeconomic scenarios and adaptation approaches for the grid (KM 23.4). Changes are based on a very high scenario (SSP5-8.5). Figure credit: Pacific Northwest National Laboratory.

Peak Power Demand

Temperature changes and extreme events alter peak power demands, driving the need for additional investment in energy infrastructure of 3%–22% by 2100.[99] Electricity needs for cooling buildings are projected to increase energy demands through 2050.[100,101,102] By 2050, warming summer temperatures are expected to increase residential electricity demand greatest in the South and Midwest, whereas warmer winter temperatures will reduce residential natural gas demand most in the South.[102,103] By the end of this century, the maximum summer cooling energy demand in the US could increase by 27% under a very high scenario (RCP8.5).[104]

Extreme events are expected to increase residential and commercial cooling demands,[100] placing additional stress on the power grid. Cooling demand in summer accounts for 30%–50% of the total daily electricity usage for the metropolitan areas of Sacramento, Los Angeles, and New York City. For every 1.8°F (1°C) of ambient temperature increase, daily electricity usage increases 6.2% in Sacramento, 4.7% in Los Angeles, and 5.1% in New York City.[105] During the 2021 heatwave in the Pacific Northwest, inland temperatures reached 120°F.[106] In Portland, Oregon, peak electricity demand was one-third higher in 2021 than in either of the prior two years.[107] Heatwaves will increase summer electricity demands if they lead to adoption and use of air-conditioning.[108]

Oil and Gas Demand

Demand for oil and gas is projected to remain stable in the US through 2050, with technological advances including electrification and electric vehicles reducing potential consumption.[3] However, with high international demand for liquified natural gas, US production may rise, and the US will remain a net exporter of natural gas. Methane emissions associated with increased natural gas production will need to be addressed (Ch. 32).

Key Message 5.2

Compounding Factors Affect Energy-System and Community Vulnerabilities

Concurrent changes in technologies, policies, and markets, in addition to their interconnections, can reduce GHG emissions while also increasing vulnerabilities of energy systems and communities to climate change and extreme weather (*very likely*, *very high confidence*). Compound and cascading hazards related to energy systems and additional stressors, such as cyber and physical threats and pandemics, create risks for all but disproportionately affect overburdened communities (*very likely*, *very high confidence*).

Decarbonization

Climate change is driving decarbonization efforts across the Nation, transforming the energy system through increased electrification and applications of wind and solar, hydrogen, bioenergy, modular nuclear, geothermal, hydropower, other long-term storage, and CCUS. Innovative energy market designs are being advanced to accelerate decarbonization. Under decarbonization scenarios that reduce economy-wide carbon emissions by at least 50% by 2030, electricity demand is expected to increase, led by transportation electrification. Demand increases vary across models from 2%–56% higher in 2030, compared to 2019 levels.[109] Projections of growing electricity demand in transportation vary from less than 10% to nearly 100% of sales by 2050,[95,96,110,111] depending on future regulations, incentives, and market acceptance. Additional electrification opportunities exist in buildings, including space and water heating, and in industry, including heat pumps and waste-heat recovery.[112,113] Replacing older air-conditioning equipment with heat pumps can improve energy efficiency for space cooling and heating, and demand-side management can reduce GHG emissions by shifting loads strategically in time.[114]

Clean hydrogen, produced with low-carbon energy, including renewable and nuclear, can help decarbonize transportation and industry (Ch. 32).[115,116,117,118,119] CCUS can reduce the carbon intensity of electricity production and combustion in industry and can be paired with bioenergy to yield additional carbon reductions.[120,121]

Rapid deployment of decarbonization technologies will create additional challenges (KM 32.2).[122,123,124] For example, vehicle electrification requires expansion of electric vehicle and battery manufacturing capacity, development of charging infrastructure, expansion of transmission, adaptation of refining operations to reflect lower demand for gasoline and diesel, and emergence of industries for recycling, repurposing, or disposing of end-of-life batteries (KM 13.4).[125,126] Vulnerabilities to climate change may increase with decarbonization; for example, a greater reliance on electricity and bioenergy could exacerbate the impacts of power outages and droughts.[85,127]

Consumer behaviors and social norms influence the adoption and actual performance of decarbonization technologies, such as home energy management systems and rooftop solar.[128,129,130,131] More efficient technologies can decrease costs to consumers, increasing activities such as driving and space heating.[132]

Resource Constraints

Global disruptions, such as the COVID-19 pandemic,[133,134] cause shortages of materials and available workforce, limiting the transition to energy system decarbonization. Some energy technology supply chains, particularly solar PV and electric vehicle batteries, are more susceptible than others to resource constraints (KM 13.4).[135,136] Island communities are especially vulnerable and slow to recover when supply chains are severed by extreme events (Ch. 23).[137]

Critical materials, such as rare-earth minerals used in batteries and electric motors, are predominantly extracted and produced outside the US (Figure 17.2; Ch. 32). Geopolitical and environmental factors influence how these materials are extracted, used, and recycled (Focus on Risks to Supply Chains).[138] Securing reliable, environmentally sustainable domestic sources of critical minerals is a national priority given the growing demand for low-carbon energy technologies.[139]

Energy system expansion to meet future demands requires suitable land, which may be limited by climate change.[140] As demand for new generation and transmission grows, integrated land-use strategies are emerging to support multiple objectives, including increases in food security, local manufacturing, and energy system resilience, as well as land and water conservation. Examples include combining solar energy with agriculture or mounting solar panels on floating structures.

Vulnerable Communities and Equity

Overburdened communities are disproportionately affected by climate impacts and energy injustice. These populations suffer more from power outages,[141] high energy prices, and health concerns from pollutants and wastes produced by fossil fuel power plants and refineries.[142,143,144,145] After Hurricane Ida (2021), areas with high proportions of Black residents had longer waiting times for power to be restored.[61] Indoor CO_2 levels associated with fossil fuel combustion have been linked to reduced human cognition (Ch. 15).[146] Overburdened communities may benefit most from decarbonization and increased energy system resilience.[147,148,149,150,151]

Extreme heat disproportionately impacts overburdened communities,[149,152] especially in urban locations where asphalt is plentiful and trees are rare.[108,153] Lower-income households that do not have or use air-conditioning are at higher health risk, such as witnessed during the unprecedented heatwaves in the Pacific Northwest (Ch. 15).[108,154]

Communities without access to reliable power are more susceptible to hazards from extreme weather events. Following Hurricanes Irma and Maria (2017), rural areas in Puerto Rico and Florida had longer power outages and slower restoration times.[141,155,156] A lack of adequate insulation accentuated effects of the 2021 winter storm in Texas on Black communities of low socioeconomic status.[157] Power outages can increase

injuries and deaths from carbon monoxide poisoning through use of gasoline-powered generators, charcoal grills, and kerosene and propane heaters inside homes lacking proper ventilation.[158,159]

Energy burden (energy cost as a percentage of household income) is an indicator of community and household vulnerability.[143,160,161,162] Nationally, rural low-income households experience the highest median energy burden at 9% (with some regions as high as 15%), compared to 3% for rural middle- and high-income households and compared to lower values for metropolitan households.[163]

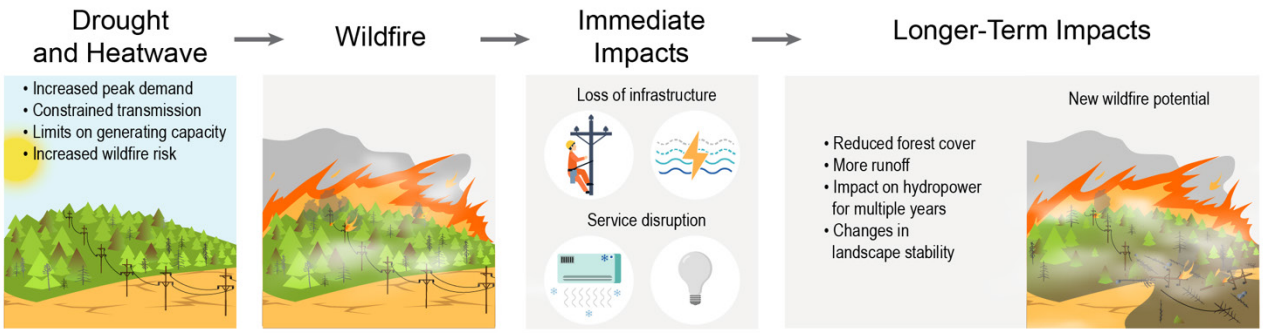
Energy inequities can be associated with lower-carbon energy sources. While the energy transition will create new economic opportunities, communities and individuals relying on employment and tax revenues from coal, oil, or natural gas can become more economically vulnerable. Individuals who held fossil fuel jobs may have difficulty finding a new job because of skills gaps, wage loss, long-distance commutes, or the need to relocate.[164,165] The number of solar and wind energy construction jobs in former coal communities may not be sufficient to replace the supply of former coal jobs.[166] Reuse of existing fossil fuel infrastructure to transition to clean energy sources may allow economically vulnerable communities to transition in place.[167] Employment and wage losses in fossil fuel sectors could be offset by increases in low-carbon resource industries,[168,169,170] although counties in Appalachia, the Gulf Coast region, and the intermountain West are expected to experience the most significant impacts, including to local services, as the tax base diminishes.[105,171,172]

Compound and Cascading Hazards

Climate change poses acute and chronic hazards to the energy system and communities from coinciding or sequential trends and extreme events (Figure 5.3; Ch. 18). Climate projections for 2041–2050 show increased power demand in Texas at the same time power supply may decrease, due in part to potential decreases in renewable resources such as wind, as well as reductions in output power from thermoelectric power plants due to warmer ambient temperatures.[173] Sequential events can compound impacts if recovery has not occurred before the next event or hazard.[174,175] Vulnerable communities near Houston, Texas, were adversely affected by the 2021 winter storm before they had recovered from Hurricane Harvey in 2017.[157] Some areas may be more vulnerable to compound hazards; for example, urbanization exacerbates or combines with flooding to compound effects on coastal infrastructure.[176]

Cyber and physical risks can add to the vulnerability of the power grid to climate change and extreme weather, especially if these events coincide.[177,178] Cyber and physical attacks are sometimes intended to compound damage to the power grid caused by extreme events.[179] Multidirectional flows of data, fuels, and electricity increase vulnerabilities. Furthermore, increased renewable energy penetration and distributed energy systems (technologies that generate electricity at or near point of use) are new variables affecting risk of power outages during extreme events.[177,178] New methods are available to assess power system vulnerability to these stressors and to quantify resilience.[180]

Consecutive and Cascading Events Involving the Energy System



Sequential and concurrent climate impacts have near-term and long-term effects on electricity generation and distribution.

Figure 5.3. Drought and heatwaves can reduce electricity generation and delivery through cascading mechanisms. Droughts reduce water availability and electricity generation. Stressed vegetation, including tree mortality following insect outbreaks, fuels wildfires. Concurrently, heatwaves increase electricity demand and reliance on transmission, which can also trigger wildfires. Wildfires damage electricity infrastructure, disrupting power and associated services. Reduced vegetation increases runoff, resulting in floods and landslides and increased risk of wildfires. The cycle of events can accelerate, as new vegetation is more sensitive to droughts and heatwaves. Figure credit: Oak Ridge National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory.

Cascading hazards can cause additional burdens to the energy system. For example, intense rains over areas burned by wildfire are projected to increase in California, intensifying flooding challenges for energy infrastructure.[181] Summer cooling demand resulting from warmer temperatures sometimes coincides with reduced hydropower due to alterations in timing of peak streamflow.[182] Additionally, flooding followed by high temperatures that increase cooling demands can overwhelm the power grid.[183]

During the 2021 winter storm in Texas, extreme low temperatures caused high demand for electricity and fuels, equipment failures in fossil and renewable generation, and supply chain disruptions (Box 26.2).[24,85] Natural gas wells and gathering lines froze, compressor stations experienced power outages, and power plant equipment malfunctioned.[24] Disruptions to power supply and delivery triggered cascading failures in other critical sectors, including municipal water supply and medical services.[24,184] At least 210 deaths resulted from the outages and cold weather.[185]

Key Message 5.3

Efforts to Enhance Energy System Resilience Are Underway

Federal, state, local, Tribal, and private-sector investments are being made to increase the resilience of the energy system to climate-related stressors, and opportunities exist to build upon this progress (*very high confidence*). Ongoing investments will need to include improvements in energy-efficient buildings; technology to decarbonize the energy system; advanced automation and communication and artificial intelligence technologies to optimize operations; climate modeling and planning methodologies under uncertainties; and efforts to increase equitable access to clean energy (*very high confidence*). An energy system transition emphasizing decarbonization and electrification would require efforts in new generation, transmission, distribution, and fuel delivery (*very high confidence*).

Activities to increase energy system resilience include upgraded grid design, hardening of energy infrastructure, vegetation management to reduce wildfire[186,187] and trees falling on powerlines,[188] and clean energy microgrids for communities vulnerable to power outages.[189] Battery storage combined with solar PV can improve building resilience during power outages.[190] Strengthening natural gas pipelines, as well as conducting periodic stress evaluation and maintenance, reduces risk from subsidence.[69] Options for oil production include providing heated water systems at drill sites to prevent freezing and upgrading platform rigs to be resilient to hurricanes.[191] Multiple opportunities are available for climate risk management in the electric utility industry,[192,193,194] with some states (e.g., California, Oregon, and New York) requiring electric utilities to conduct climate vulnerability assessments (KMs 21.4, 32.5).

Improved Climate Modeling to Inform Planning for Energy System Resilience

Improved accuracy, detail, and modeling capabilities are allowing high-resolution Earth system models and human–Earth system models to help decision-makers reduce vulnerabilities to climate change and inform energy system plans and operational strategies across spatial scales.[14,45,195,196,197,198] For example, identifying where storm surge may threaten energy infrastructure could lead to fortifying or moving that infrastructure.[199] Projections of the severity and duration of future droughts could guide decisions to reduce water demand for energy supply.[200,201]

Modeling advances are improving understanding of climate impacts and wildfires on transmission lines[165,202] and solar PV,[21] stream temperature for thermoelectric power plants,[52] and water availability for the production of hydropower[45] and hydrogen.[203] Model applications include estimating lost power and restoration costs from hurricane damage.[204] Studies have investigated integration of climate-related impacts into long-term planning to achieve resilience to future extreme events.[39,205,206,207,208]

Efforts are underway to understand the range of climate impacts on interconnected energy systems, including improvements to multisector models,[209,210] observations[48] and analytics,[182,211,212] and development of Earth system models with advanced climate–human feedbacks.[213] Analyses of extreme events such as the 2021 extreme cold event in Texas,[85] the cascading power outages in California in 2020, and Hurricane Maria in Puerto Rico in 2017[214] can be used to plan and design for cross-sector resilience.

Addressing Compound Threats

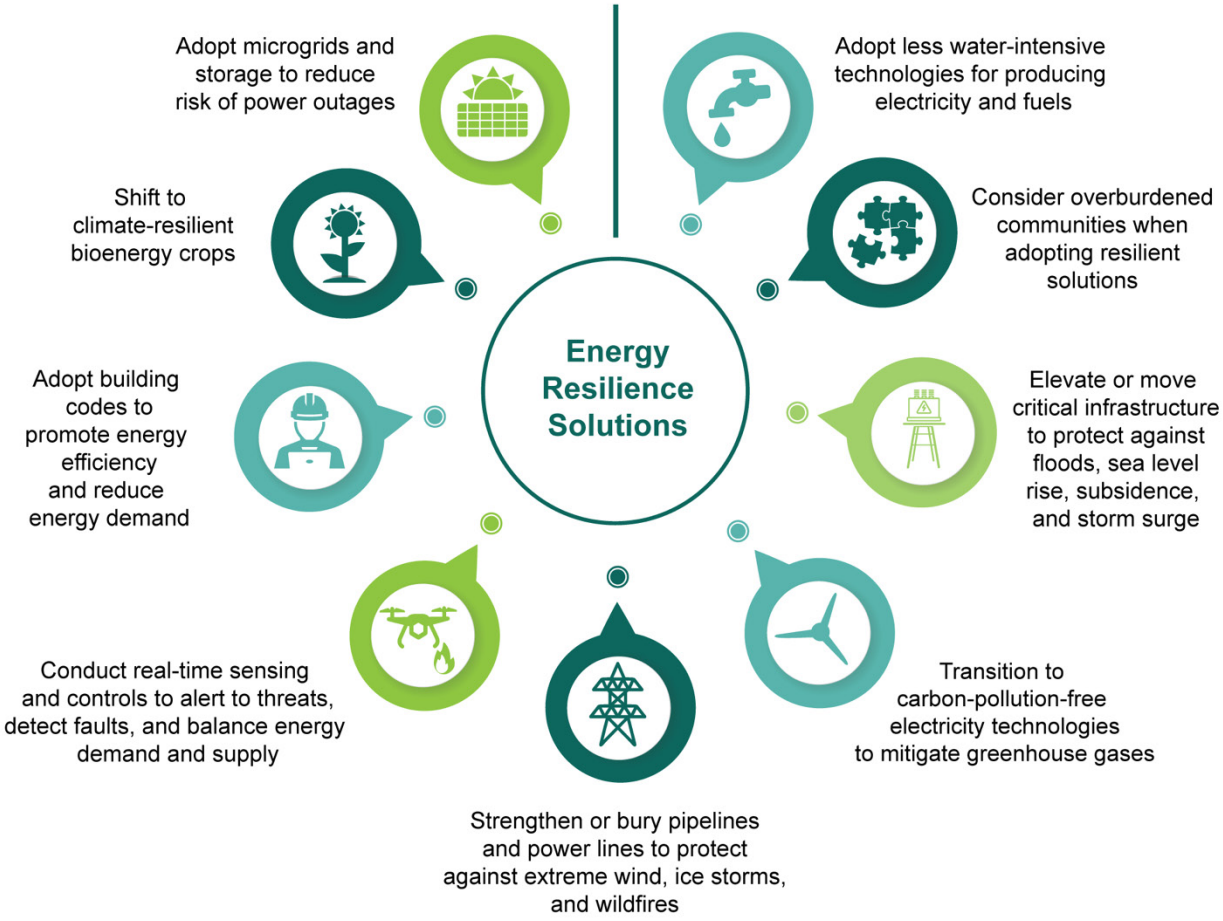
Progress is underway to develop and implement solutions addressing energy system risks from compounding impacts of climate change and threats from pandemics (COVID-19), cyberattacks,[177,215,216] electromagnetic pulse events,[85,174,176,180,217] market shocks,[218] and supply chain disruptions (KM 5.2). Examples include holistic modeling and analyses that reflect the interconnectedness of energy and water systems and the design and operation of energy systems that account for combined effects of climate trends and extreme weather events.[205,219]

Hardening Energy Systems to Reduce Vulnerabilities to Climate Change

Energy system design and operations are being hardened to reduce vulnerabilities to climate change (Figure 5.4). Examples include elevating or moving equipment to avoid floods, strengthening pipelines and powerlines or moving them underground to reduce wind or ice damage and risk from wildfire, and recycling cooling water and deploying dry cooling technologies to reduce power plant susceptibility to drought.[220] Improving building codes can bring changes (e.g., grid-interactive efficient buildings, cool roofs, resilient construction materials) to the built environment (Ch. 12), enabling energy and emissions reductions (Ch. 32) and technologies (e.g., adaptive buildings, PV-ready buildings; Ch. 31) to advance resilience to climate change. Drones and sensors identify wildfire risks in real time, allowing protective actions to be taken.[221]

New tools and models are available for identifying infrastructure vulnerabilities and storm probabilities and for identifying effective hardening approaches,[214,222,223] including accelerated infrastructure investments to improve resilience of coastal systems to storm events.[224]

Potential Energy System Resilience Solutions



Many strategies are available to increase energy system resilience to climate change.

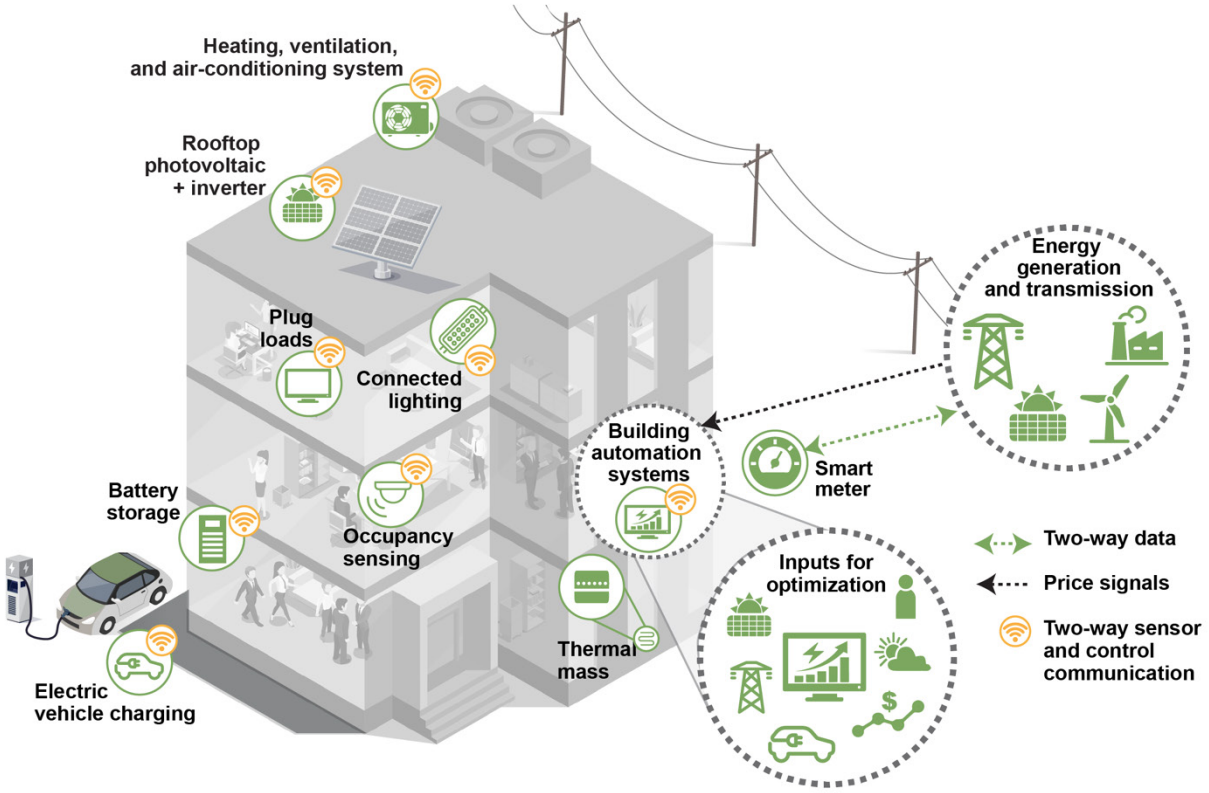
Figure 5.4. While climate change results in risks to the energy system, many approaches for enhancing energy system resilience are available. Resilience options include burying powerlines, elevating critical infrastructure, Introducing microgrids and distributed generation, and improved monitoring. Figure credit: EPA, FEMA, and DOE.

Automation, Information Technologies, and Grid-Interactive Efficient Buildings

Advances in sensing, smart metering, and internet-connected appliances have enabled real-time monitoring of energy systems. Machine-learning algorithms are facilitating insights into energy supply, demand, and operations.[225] The electric grid can be more resilient to climate stressors if future renewable energy generation is better forecasted, operational faults are detected and diagnosed, supply and demand are balanced to account for variable generation and vehicle charging, and cyberattacks are detected.[226]

Grid-interactive efficient buildings (Figure 5.5) apply energy efficiency, smart technologies, and flexible load management.[227] Advanced control systems[228,229] predict energy demand in real time and maximize efficiency, minimize cost, and lower carbon emissions of HVAC systems. Application of natural gas demand response to residential heating during extreme cold conditions is projected to reduce demand by up to 29%.[86] By reducing and shifting the timing of electricity consumption, grid-interactive efficient buildings could decrease carbon emissions by 80 million metric tons per year by 2030, or 6% of total power sector carbon emissions.[227]

Grid-Interactive Efficient Buildings



A reimagination of building design and operation is being driven by decarbonization goals.

Figure 5.5. Grid-interactive efficient buildings (GEBs) integrate energy efficiency technologies (HVAC, plug loads, lighting), on-site renewable energy (photovoltaics), electric vehicles, and electric storage with smart sensing (HVAC, lighting, and occupancy) and control optimization to enable demand flexibility and provide excess electricity to the power grid through the smart meter when demand exceeds supply or when supply from the grid is constrained. The building automation systems can import the grid electricity pricing and carbon-intensity factor in real time and communicate the potential to reduce demand to the grid through the two-way sensor and communication protocol. Adapted from Nubbe and Yamada 2019,[230] © 2019 Guidehouse Inc.

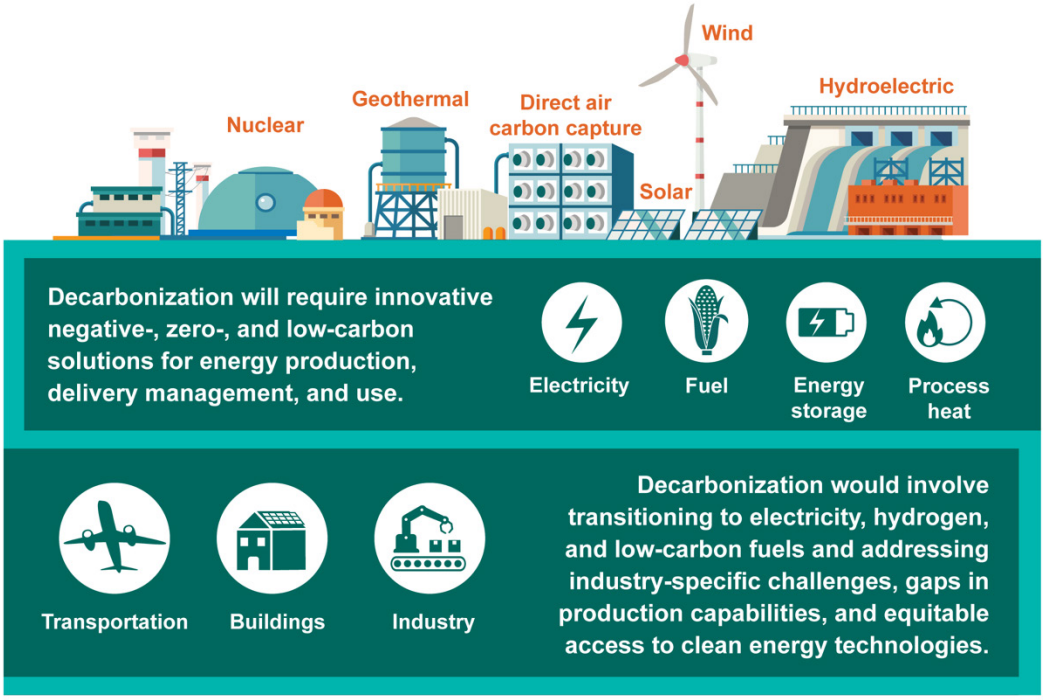
Technology Development and Deployment to Decarbonize the Energy System

A major transition is underway to decarbonize major economic sectors (Figure 5.6),[231,232,233] supported by policies (e.g., mandates to reduce fossil fuel use, tax incentives), falling costs, and technology innovations. Significant advancements in low-carbon energy technologies have been made in the electricity sector.

Growth in electric power demand is projected due to increasing electrification and ongoing economic growth. Declining capital costs and government subsidies, including IRA initiatives, are projected to drive increasing renewable energy generation from solar and wind by about 325% and 138% respectively, by 2050 as compared to 2022.[3] Increased electrification of end-use sectors is projected with the adoption of more heat pumps and electric vehicles, as well as electric arc furnaces in the iron and steel industry.

Some technologies can provide energy benefits to other sectors. For example, nuclear power produces thermal energy that can be used in industrial applications, substituting for fossil fuels. In addition to reducing energy-related emissions, electricity may be more reliable, efficient, and economical compared to other energy sources.[95] High electrification rates could be supported by greater integration of renewables.[93,234]

Energy System Decarbonization

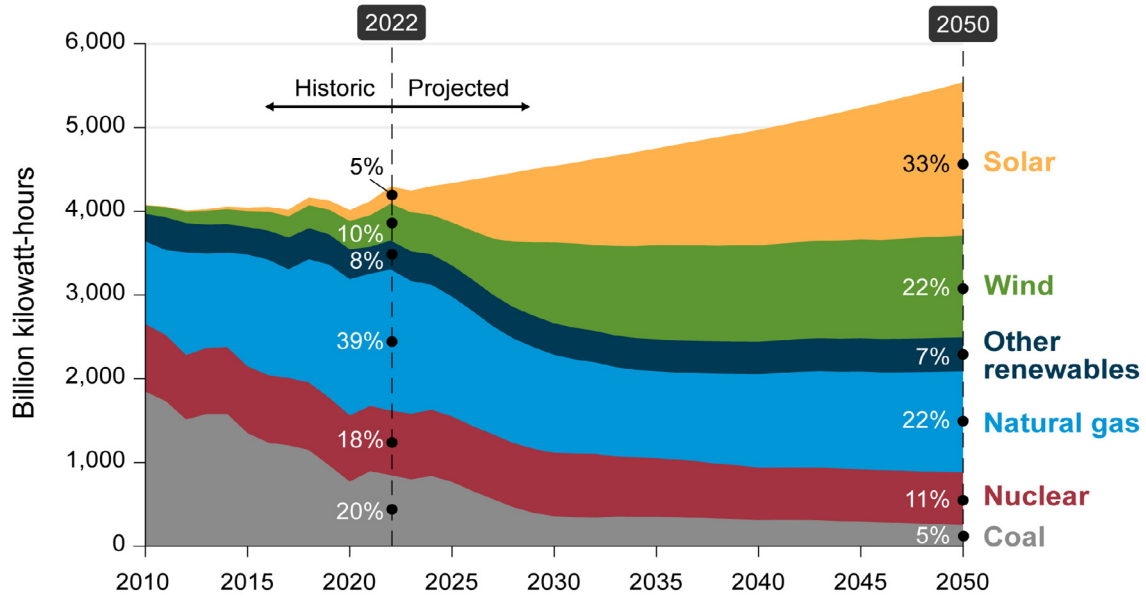


Decarbonization will require innovative solutions across multiple sectors.

Figure 5.6. Energy system decarbonization will rely on increased innovation, deployment of clean energy technologies including carbon capture, small modular nuclear reactors, hydrogen, and further integration and electrification of residential and commercial buildings, industry, and transportation. Figure credit: DOE, Idaho National Laboratory, NOAA NCEI, and CISESS NC.

With wind and solar costs dropping 70% and 90%, respectively, over the last decade, capacity additions are reaching historic levels[235] and are projected to increase (Figure 5.7).[3,112,236] Advances contributing to cost reduction include technological advances, improved efficiency in energy generation and manufacturing, reduced capital costs, and accumulation of operational experience. However, greater transformation is needed to meet goals of 100% clean electricity in 2035 and net-zero GHG emissions by 2050.[237] Meeting both goals requires electrification of transportation, buildings, and industry and production of low-carbon electricity from renewable, nuclear, and fossil fuel energy with carbon capture.[112,123,238] The rate of decarbonization will be determined, in part, by public acceptance of new energy technologies and infrastructure.[239]

Historic and Projected US Electricity Generation Sources



The Nation's electricity grid continues to expand use of clean energy technologies.

Figure 5.7. Most electricity generation projections see significant growth for renewable sources. Recently enacted legislation is anticipated to increase deployment rates for low-carbon technology. Adapted from EIA 2023.[3]

Advances are being made in performance and cost for other energy technologies. Over the last decade, costs of lithium-ion batteries for electric vehicles have dropped 85%,[240] and progress is being made to recycle batteries and develop alternative materials beyond lithium. Efforts to lower production costs for clean hydrogen by 80% to $1 per kilogram could unlock new markets and create jobs in industries such as steel manufacturing, clean ammonia production, energy storage, and heavy-duty trucks.[241]

Demonstrations for advanced small modular nuclear reactors have begun with design approval from the US Nuclear Regulatory Commission,[242] as well as efforts to use existing nuclear power plants and fossil-fueled power plants with carbon capture to generate clean hydrogen and purify water in addition to producing electricity.

Solutions for Vulnerable Communities and Energy Justice

Policies related to energy system decarbonization can promote energy equity. Procedural justice, which relates to equitable participation in and influence on energy decisions,[243] is key to equitable energy solutions. Opportunities to promote energy equity and reduce energy burdens include collective, inclusive decision-making around utility-initiated power shutdowns; adopting energy storage with decentralized solutions, such as microgrids or off-grid systems;[73] developing community-sharing opportunities for solar energy (including rooftop solar) and energy storage;[144,244] and building emergency cooling or heating shelters to serve overburdened communities.[245] An example of a Tribal community addressing a just transition from fossil fuels to renewable energy is the Blue Lake Rancheria Tribe's large-scale solar and microgrid project.[223,246]

Many decarbonization technologies are expected to decrease environmental impacts such as air pollution (KMs 14.5, 32.4),[247,248,249,250] potentially benefitting overburdened communities that disproportionately experience pollution from roadways, refineries, and power plants.[251,252,253] However, impacts of some decarbonization technologies can shift the magnitude, location, and type of pollution (KM 32.4).[254,255,256,257] Environmental regulations and permitting requirements play an important role in addressing impacts.

Energy burden remains high for overburdened groups. Many policies and programs that promote clean energy or energy efficiency are inaccessible to low-income households.[258] Policies that fix energy prices during extreme events or prioritize energy restoration for overburdened communities can provide more equitable support.[184] Federal assistance programs can help communities overcome climate challenges and enhance resilience (Ch. 31).[259] In addition, federal programs are being established to promote energy equity and serve overburdened communities.[260,261]

Traceable Accounts

Process Description

The author team was selected to bring diverse experience, expertise, and perspectives to the chapter. Some members have participated in past Assessment processes. The team's diversity appropriately reflects the spectrum of current and projected climate impacts on the Nation's complex energy system, the energy system's roles in national security and economic well-being, and the need for equitable access to reliable and affordable energy and environmental justice. The all-federal composition of the author team was a decision of the National Climate Assessment (NCA) Federal Steering Committee. The author team has demonstrated experience in the following areas:

- characterizing baseline supply and demand for electricity and fuel from diverse sources at multiple scales;
- characterizing effects of climate on the energy sector—as well as opportunities for climate change mitigation and options for increasing resilience to climate-related stressors—at national, regional, state, and local levels;
- developing and implementing energy system models for projecting technology deployment, fuel use, and greenhouse gas (GHG) and air pollutant emissions over wide-ranging scenarios;
- analyzing energy system sensitivities to drivers such as policy, markets, technology, and physical changes;
- developing and implementing climate science models, tools, and information for characterizing energy sector risks;
- supporting local, state, Tribal, federal, and private-sector stakeholders in integrating climate change issues into long-range planning and project implementation;
- assessing the environmental impacts of new and emerging energy technologies; and
- analyzing technological, societal (including justice), economic, and business factors relevant to risk reduction and energy system resilience.

The author team met virtually on a weekly basis to develop the chapter, address issues, and build consensus. In addition, the team met with representative authors from other chapters to identify and address cross-cutting issues. To ensure the chapter is informed by and useful to stakeholders, a public engagement workshop was held to provide participants an opportunity to exchange ideas with the author teams on chapter key topics, share resources, and give feedback on issues of importance to them. Participants in the workshop represented government (federal, state, local, and Tribal), nonprofits, academic institutions, businesses and the private sector, community groups, students, and others.

To develop Key Messages, the team conducted searches of the scientific literature, including peer-reviewed journal articles, government reports, and reports of nongovernmental organizations, as well as incorporating input from the workshop. The team drew on measurements (e.g., data on ongoing effects of past extreme events and government energy data); model outputs (e.g., from climate models, models of energy supply and demand, models of climate effects, and models of resilience of climate change stressors on the energy system); published perspectives of experts, some of which identified sources of uncertainty; and input from the workshop and from peer reviewers of this chapter. The chapter does not reference newspaper articles.

Key Message 5.1

Climate Change Threatens Energy Systems

Description of Evidence Base

The impact of increased concentrations of greenhouse gases (GHGs) on global warming (Ch. 2) and sea level rise (Ch. 3) is well established in the peer-reviewed research and supporting publications, and the impact of climate change on extreme events is growing (Ch. 3). Mechanisms by which climate change impacts energy infrastructure and electricity demand also have a strong research foundation, with extensive documented analyses of climate trends and past extreme events, as well as peer-reviewed research on projected impacts that uses empirical data[262] or downscaled climate projection data[29,263] and detailed models of possible future energy system designs.[264] One new study linked the output of global climate models to a weather forecasting model to project regional energy effects.[32] The importance of extreme events has required new types of empirical models, some of which are integrated with climate models or outputs (e.g., the relationship between smoke and photovoltaic capacity or productivity).[21,22] Historical data on hurricanes are combined with ocean models to better understand variables important to offshore wind energy.[13] New econometric models based on weather variables, consumption data, and population growth estimates are also important components of the evidence base related to electricity demand projections.[103] There is strong agreement in the literature on mechanisms and types of electricity demand impacts,[265] although impacts are expected to differ by location.[103] The magnitudes of projected energy system impacts are dependent on the magnitude of climate change and the increased rate, magnitude, and location of extreme events (KMs 23.4, 27.4). There is a foundation of regional-level studies on how the energy system is being impacted and is projected to be impacted[31,32] and, ultimately, how those impacts may affect energy users locally. Where and when these impacts will occur locally is much harder to model in the context of temperature and precipitation trends and especially in the context of extreme events than at the more regional and continental scales.[8]

Major Uncertainties and Research Gaps

Much of the key evidence related to extreme events is empirical and opportunistic. Although significant data are available to document the effects of extreme events on energy systems, those data and analyses are typically published two to four years after the event. For example, at the time this report was written, important papers were still being published on infrastructure and energy justice effects of Hurricanes Harvey, Irma, and Maria in 2017.[82,141,155,157] Most analyses of the impacts of Hurricane Ida in 2021 will not be available for several years, although Coleman et al. (2023)[61] is an exception. Opportunities exist for more timely assessments of major impacts of extreme events on energy systems to inform relevant policy discussions, investments, and efforts to increase energy system resilience and human adaptation.

There is more confidence in national projections of climate variables and extreme events than in estimates of local impacts. Therefore, the authors are confident that the frequency and intensity of extreme events will increase nationally (Ch. 2) but not as confident in the locations of specific events that may impact energy supply and demand over the coming decades.[13,266] Similarly, projections of wind power are only as good as the often-coarse spatial and temporal resolution of the climate models used.[31] The authors are confident that the demand for cooling buildings in summer will increase in most regions across the continental United States.[103] In studies where climate projections are downscaled, computational demands and data storage requirements limit the number of projections that can be used and therefore increase uncertainty, as recognized by cited authors.[263] Cost projections for physical damages to infrastructure do not include those from floods, high winds, and ice storms, which are poorly represented at the coarse spatial scale of climate models.[57]

Furthermore, in the studies cited, there is sometimes disagreement among researchers. Whereas emerging research suggests that the frequency of cold-weather events and heavy snowfall may be increasing because

of warming Arctic temperature,[267] there is some disagreement in the research community[268,269] regarding this projection and the impact such a change may have on increasing or decreasing future heating demands regionally. Furthermore, there is uncertainty regarding future wind resources and trends.[31,262,270]

Many model inputs are uncertain. For example, potential bioenergy projections are dependent on uncertain CO_2 fertilization intensity.[30] Furthermore, projections of electricity and natural gas demand are sensitive to socioeconomic factors, such as the ratio of urban to rural population or changes in energy prices that may reflect the pace of shifts in energy technologies.[103]

Description of Confidence and Likelihood

Based on historical data, recent trends, modeling projections, and attribution analytics, there is *very high confidence* and it is *virtually certain* that climate change and extreme weather are negatively impacting the Nation's energy system and that, unless action is taken, climate change will continue to affect the energy system, including damaging energy infrastructure and operations. There is *very high confidence* that energy supply and delivery are at high risk from climate-driven changes,[271,272] including shifts in demand,[45,273] damage to infrastructure and operations,[271,274] and resulting effects on human lives and livelihoods. It is *virtually certain*, based on past experience and modeling projections, that climate change trends will continue (Ch. 2), and effects on energy systems will vary over time and location and increase with projected increases in the frequency, intensity, and duration of extreme weather threats, including extreme precipitation, extreme temperatures, sea level rise, and more intense storms, droughts, wildfires, and thawing of permafrost.

Key Message 5.2

Compounding Factors Affect Energy-System and Community Vulnerabilities

Description of Evidence Base

Decarbonization

There is growing evidence from peer-reviewed analysis demonstrating both the need for and progress in decarbonization of the energy system through increased electrification and applications of clean energy, including wind and solar; hydrogen, bioenergy; modular nuclear; geothermal; hydropower; other long-term storage; and carbon capture, utilization, and storage (Ch. 32).[95,96,109,110,111,112,113,114,115,117,118,119,121] However, additional studies are needed to better characterize how the rapid deployment of decarbonization technologies will create additional compounding challenges (KM 32.2),[122,123,124] including the need for additional energy infrastructure associated with expansion of electrification demand (including generation, transmission, and distribution), expansion of electric vehicle and battery manufacturing capacity, development of charging infrastructure, adaptation of refining operations to reflect lower demand for gasoline and diesel, and emergence of industries for recycling, repurposing, or disposing of end-of-life batteries (KM 13.4).[125,126] More information is also needed to better characterize consumer behaviors and the cost and performance of decarbonization technologies, which will influence the pace, scale and scope of their adoption by society.[128,129,130,131,132] Opportunities exist for better characterizing the co-benefits of both reducing GHG emissions and increasing climate resilience through decarbonization, including, for example, quantifying the benefits of deployment of distributed clean energy generation with microgrids and storage that reduces emissions and provides backup generation during power outages.

Resource Constraints

Whereas there is abundant research and industry knowledge on global supply chain dynamics, commodity markets, and strategic materials, there is less peer-reviewed literature focusing specifically on the current

and anticipated future supply chain and resource constraints associated with those parts of the energy system that are gaining, or anticipated to gain, greater market share in the energy economy, including electric vehicles, wind and solar energy, and battery storage. Research is lacking in this area, including on the relationships and sensitivities across parts of the energy sector that may be competing for the same source materials, as well as on the potential for alternative materials or processes that may help address supply chain constraints or risks, particularly where sectors other than energy may be competing for similar feedstocks, materials, or personnel.

Cyber and Physical Threats to the Power Grid

A growing body of peer-reviewed research related to cyber/physical security argues for the joint consideration of climate change and cyber/physical attacks in grid analyses and resilience responses.[177,178] However, many data-driven analyses of actual system incidents, response measures, and defenses are not publicly available and therefore are not referenced. There is growing research on human and environmental threats to the power system, how they relate to each other, and how multiple objectives like decarbonization of the energy system, system resilience to climate stressors, and cyber defenses can be optimized as the energy generation mix changes and threats evolve across the grid and other energy infrastructure.[177,178]

As with cybersecurity, a significant amount of non-peer-reviewed analysis related to compound and cascading hazards and threats is occurring in the classified domain, particularly in those cases that involve a human threat or cyber incident. Furthermore, anecdotal news reports refer to consecutive extreme events, but insufficient peer-reviewed evidence is available to indicate whether some of these compound threats are increasing, that there is a causal association between them, or that they have a compounded effect on energy systems. In addition, while information is available on characterizing the benefits of a smart grid system that can automatically reroute power to electrical systems that are most needed to minimize impacts of outages, opportunities exist to better characterize the unintended consequences of a smart grid system and its increased susceptibility to extreme weather and cyber threats.

Vulnerable Communities and Equity

An abundance of peer-reviewed research on environmental justice relates to the placement of fossil fuel power sources and resultant air pollution[145] and health threats in or near overburdened communities. A growing body of evidence shows that overburdened communities are disproportionately affected by the impacts of climate change, including resource-constrained abilities to migrate and low access to high-quality infrastructure such as air-conditioning.[275] Furthermore, inequitable exposure to heat islands in cities is addressed by analysis in the peer-reviewed literature.[149,152] More information is available on inequities in electricity delivery (e.g., energy access, energy burden,[162] and electricity restoration times[61] than on inequities in supply or on differential demand (including cooling-system-use temperatures[154]) in response to climate change and extreme events.

Compound and Cascading Hazards

There is a growing body of peer-reviewed research focused on understanding climate, ecosystems, and human systems and implications for the energy system. Notably, significant progress has been made over the last decade to better understand the agriculture–energy–water nexus, correlated risks in these three domains, and strategies to address them. Multiple extreme events and other climate-related stressors are affecting the same regions; for example, wildfire may be followed by floods,[181] and multiple hurricanes may affect a single coastal location.[157] Climate projections show that increased demand and decreased supply of electricity will coincide in regions during heatwaves.[173] Recent extreme heat (e.g., Turner et al. 2021[55]), extreme cold (e.g., Busby et al. 2021[24]), and flooding (e.g., Collins et al. 2019[147]) events in Texas, for example, have helped advance a growing body of research to understand the relationships between the electric grid, fuel supply and infrastructure, and market design and pricing, as well as how humans respond to real-time

extreme events and how overburdened communities are disproportionately impacted.[157] These are complex, dynamic systems. While emerging multidisciplinary modeling frameworks are improving the understanding of dynamics of multisectoral systems that include energy, many opportunities exist for improving these frameworks, including improving spatial and temporal resolution, sectoral detail, cross-sector interactions, representation of factors impacting energy and environmental justice, and utilization of high-performance computing to address data and computational requirements.[174,176]

Major Uncertainties and Research Gaps

Increased multidisciplinary and cross-sectoral analysis and research can lead to an improved understanding of the compound and cascading hazards across the energy system. Because cascading threats are correlated, they may be easier to predict than compound threats, which are independent.[176] Data-driven analysis could be undertaken to inform the understanding of complex-system dynamics impacting climate risks and vulnerabilities in the energy sector that involve human behavior, markets, infrastructure, electricity, fuels, and environmental conditions.

Energy justice research results are sensitive to spatial scales of analysis.[239]

The limited sample size of localities, regions, or sectors that have achieved their decarbonization or electrification goals to date limits information that can inform analyses of climate implications for the energy system. The majority of peer-reviewed research does not address past or current efforts but rather is forward-looking, addressing potential implications and opportunities. There is a pressing need for greater insights on the near-term localized impacts of decarbonization efforts on aging distribution networks, particularly where electric vehicle penetration is growing rapidly.

Research gaps include the need to better understand global supply chain implications and relationships across those technologies or materials that will be important for mitigating climate change and increasing resilience of energy systems to climate-related stressors and events. There is also a need to better understand other resource constraints informing rapid scaling of decarbonization strategies, such as land-use optimization and trade-offs, infrastructure constraints, human dimensions of energy transitions including workforce development, and pathways for developing and using alternative feedstocks or materials, particularly those that may mitigate geopolitical or security risk. There is uncertainty regarding how cascading events will change in the future, how human activities will alter the risk of compound events, and how new infrastructure design guidelines might alter risk.[174]

Cross-fertilization of research between utilities and industry, classified domain research, and public peer-reviewed research could help researchers better understand current and future cyberthreats to the energy system, including how and where those threats may exacerbate or exploit climate change–related risks.

Description of Confidence and Likelihood

Based on a growing body of evidence, including recent trends and peer-reviewed research, there is *very high confidence* that compound and cascading hazards—many of them climate related[175,179,181]—and compounding effects of changes in technologies, policies, and markets will continue to impact the climate change vulnerability of the Nation's energy system. It is *very likely* that energy system decarbonization and increased electrification will create new and growing demands on existing electricity infrastructure and will require significant investment in new generation and delivery.[124] While these changes will reduce dependency on fossil fuel sources, it is *very likely* that, unless addressed, they will result in increased vulnerabilities and supply chain constraints.

Key Message 5.3

Efforts to Enhance Energy System Resilience Are Underway

Description of Evidence Base

Much of the evidence for this key message is qualitative, with citations in the main text. For example, energy resilience options and decarbonization technologies are described in the main text with no additional evidence here.

Evidence that efforts for energy systems are underway include legislation and states' recommendations. Overall, the energy sector is leading the way on decarbonization of the economy, with 22 states, the District of Columbia, and Puerto Rico having enacted legislation to reach 100% clean energy goals.[276] Integrated resources plans (IRPs) are required from electric utilities in 33 states that work with partners on the development of adaptation framework specific to the electric utility sectors.[277] The US Environmental Protection Agency State Energy and Environment Guide to Action[278] provides guiding framework on how to represent climate change to utilities IRPs. Cooke et al. (2021)[279] reviewed best practices in consideration of climate change of IRPs in 40 electric utilities across the US, admitting an increased level of complexity in the process. While IRPs are not legally bounding, some states such as California and New York made legislation of some recommendations. State-scale vulnerability assessments are also leveraged to develop legislation (KMs 21.4, 32.5).

The reduction of uncertainty of future climate projections is essential for future planning, human adaptation, and increasing energy system resilience, and a number of studies have demonstrated progres s.[195,196,201,209,210,280,281,282,283,284,285] Fragility curves of damage to power generating stations (coal, gas, solar, wind) and electrical grid components, as well as replacement and repair costs under hurricane scenarios, have also been developed.[204] Even in contexts where climate projections are uncertain, modeling advancements are helpful for planning; for example, modeling synthetic storms provides extreme wind and wave loads required for planning of offshore wind energy.[14]

Research is ongoing to identify needs for hardening[24] and to reduce the vulnerability of conventional energy system technologies to climate change.[191] For example, a range of studies reflects ongoing efforts by the oil and gas sector to address the challenge of a warming climate in Alaska, including technological improvements implemented in seismic exploration, operation and maintenance practices, and other improvements (e.g., use of thermosiphons, or cooling devices that will chill the ground beneath oil and gas infrastructure to provide protection from the dangers of thawing permafrost).

Significant innovations and deployment of zero-carbon electricity generation technologies are occurring, including in solar photovoltaics and on- and offshore wind. The costs and performance of batteries and long-term storage also are improving as their capacity grows to support the integration of renewables.[190] Advanced nuclear technologies (small modular reactors and microreactors) are now being demonstrated. Studies demonstrate innovative research, development, demonstration, and deployment to address large-scale carbon management. These include applications of CCUS at power plants and industries, as well as an expanding focus on carbon dioxide removal from the atmosphere through direct air capture and bioenergy with carbon capture and storage.[286,287] In addition, advances in low-carbon fuel sources can complement clean electricity, such as hydrogen (i.e., made from natural gas with CCUS or by electrolysis of water using zero-carbon electricity sources) to replace the role currently played by natural gas.

On the demand side, there is evidence of progress in reducing carbon through electrification. This evidence includes increased marketing and sales of electric vehicles and deployment of charging stations.[115,288] In addition, federal policies (e.g., efficiency and emission standards) and incentives (e.g., electric vehicle tax credits) appear to be succeeding in reducing use of fossil fuels. Furthermore, power companies are

evaluating how electric vehicles can improve resilience of the electric grid to extreme events by providing backup power during power outages.

Studies demonstrate how new technologies, cost reductions, and a range of enabling state and federal policies are contributing to the transition to a clean energy system (Chs. 25, 32).[4,5,7,8,9,10,11] However, there is inconsistency in the adoption of these policies across the Nation. For example, some states and local communities are adopting building codes, incentives, and bans to shift to clean energy sources,[10,11] while other states are adopting polices that would prohibit actions necessary to reduce GHG emissions, such as prohibiting restrictions on the use of fossil fuels. While progress is underway, actions vary from state to state in establishing an enabling policy framework to increase the pace, scale, and scope of the energy transition to deliver more clean energy and build a more resilient energy future.

Major Uncertainties and Research Gaps

Research on energy resilience, including current approaches and future methods, has gaps. Much of the resilience and long-term power planning research to date has included case studies developed in silos, and there is a need to further integrate the range of models and associated recommendations on decision-making.[289] For example, effects of increased renewables penetration on electricity system resilience, including planning, response, and restoration, are not well studied.[177] Information is limited on the implications of measures that communities are using to increase resilience to extreme events. During power outages, remote or island communities often turn to backup diesel generation for increased power. However, data on the types of measures employed and costs and benefits associated with these backup options are often lacking in current analyses. Research efforts more specific to power system models include the development of next-generation tools to create multiscale cross-domain dependencies with a strategic computational efficiency for faster adoption, which will enhance the ability to plan for the unpredictable including extreme events and cyberattacks.[289]

Much effort is ongoing in the development of Earth system models that could inform the energy sector, including the regional refined mesh capabilities to enable high-resolution simulations in the region of interest in global settings.[290] In addition, while progress has been made in the energy–environmental–social science modeling, gaps remain in understanding the complex interactions.[210] Potential areas for study and development include the energy–water nexus. Specifically, technology innovation research includes cost-competitive desalination technologies, transforming produced water to a reusable resource, reducing water impacts in the power sector, increasing resource recovery from wastewater, and developing small, modular energy–water systems.[291] Projections of future energy infrastructure under current policies as well as decarbonization pathways now systematically investigate water demands across sectors,[292] as different technologies rely on either water withdrawals or consumptive use with complex interactions and coordination with other water uses. Higher-resolution modeling is needed to address regional institutional priorities and vulnerabilities.[293]

Energy justice is a relatively new research area. Whereas researchers are beginning to record and analyze distributional injustices (e.g., differential times to power restoration for different communities),[141,155,156] the lack of understanding of supply differences and vulnerability differences limits the ability for utilities and governments to study and develop fair policies and responses. Furthermore, data at finer resolution than the census tract scale are often not available; therefore, local distributional injustices are more uncertain than injustices occurring at larger spatial scales.

Considerable research is being conducted using energy system optimization and integrated assessment models to understand the environmental impacts of various climate change mitigation strategies, including on co-emitted pollutants and air quality,[247] as well as on labor and crop impacts.[294] While these studies tend to suggest air quality benefits associated with decarbonization, some suggest that there could be shifts in

the location of pollution and potentially the introduction of new sources of air pollution.[257] Opportunities exist to improve our understanding of the air pollutant emissions associated with decarbonization technologies, the degree to which these emissions can be controlled, and the role of permitting and environmental regulations on influencing siting and control decisions. There are also opportunities for more fully understanding how the resulting changes affect vulnerable populations, such as how changes in air-pollutant emissions result in changes in neighborhood-scale impacts.

Life-cycle analysis methods can be used to provide insights into the relative environmental benefits of alternative climate change mitigation technologies and pathways, including the impacts of manufacturing energy technologies and the construction of energy infrastructure.[295] A research gap in more fully understanding environmental impacts of energy transitions could be addressed by linking life-cycle analysis methods with energy system and integrated assessment models.[254,296]

Description of Confidence and Likelihood

Research by authors in government, academia, and the private sector has produced evidence that allows the authors to conclude with *very high confidence* that enhancements in the resilience of the energy system to climate-related stressors are being made, including improvements in energy-efficient buildings; technology to decarbonize the energy system; advanced automation and communication, artificial intelligence, and machine learning technologies to optimize operations; climate modeling capabilities and planning methodologies; efforts to increase equitable access to clean energy; and federal support to communities for resilience investments. There is *very high confidence* that opportunities exist to build upon these efforts and that increases in the pace, scale, and scope of these efforts would be needed to meet the climate crisis.[87,232,233,236]

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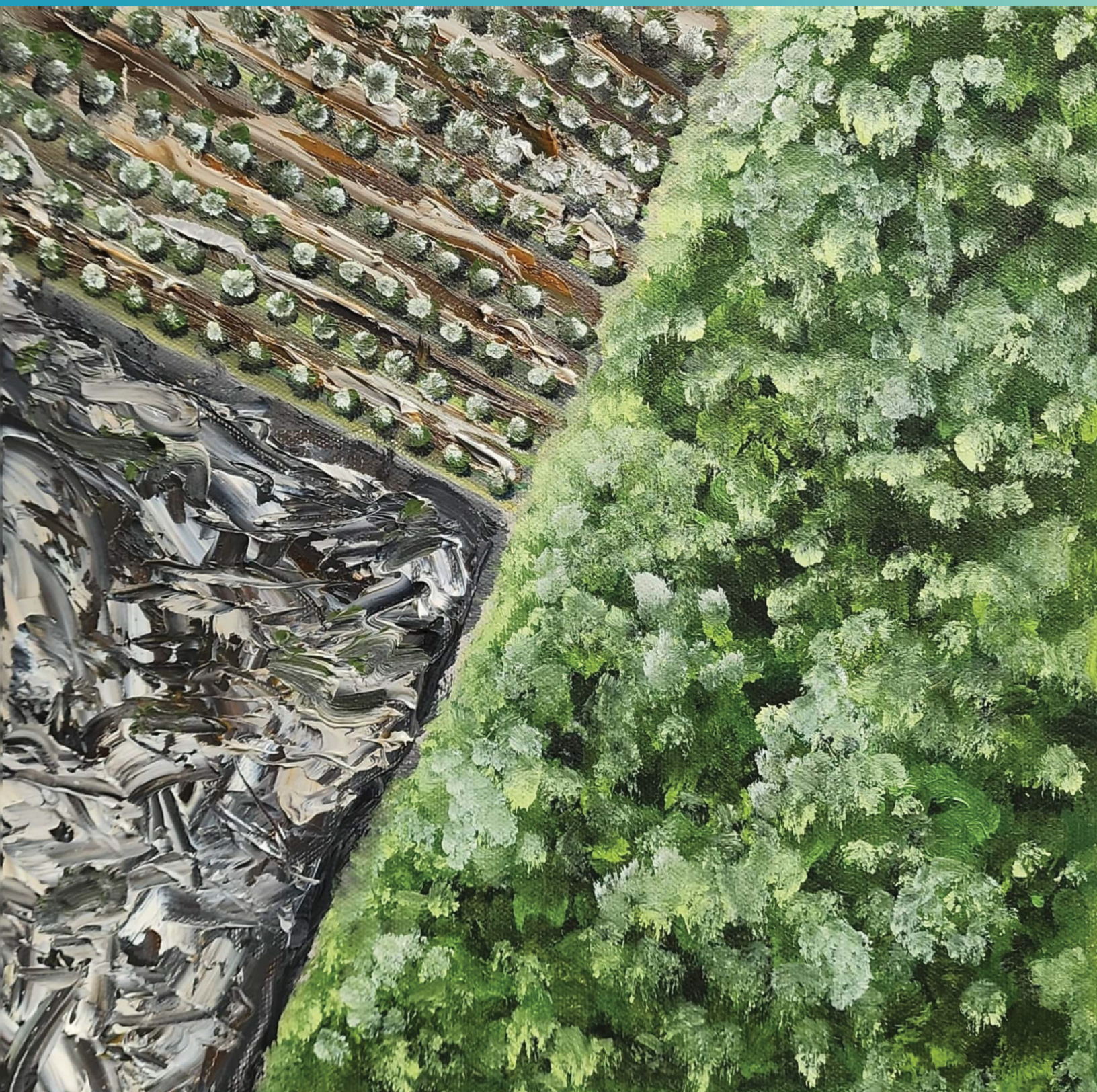
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Fifth National Climate Assessment: Chapter 6

Land Cover and Land-Use Change



Dedication

We dedicate this chapter to the memory of our friend and colleague Brad Reed. Brad served as a coordinating lead author for the Land Cover and Land-Use Change chapter before he suddenly passed away. He made groundbreaking contributions to the chapter by setting up the chapter team and chapter structure. Brad was well respected throughout the USGS and the broader scientific community and was a close friend and colleague to many. He was involved in a number of research endeavors, including mapping global land cover, characterizing phenology from Earth observation data, and assessing biological carbon sequestration for the US. Brad was a pioneer in the fight against global warming and a strong advocate for the conservation of Earth's natural resources. A leader in the land-change science and Earth observation communities, Brad made great efforts to tackle society's most urgent issues.

Chapter 6. Land Cover and Land-Use

Authors and Contributors

Federal Coordinating Lead Authors

Bradley C. Reed, US Geological Survey

George Z. Xian, US Geological Survey

Chapter Lead Author

Peter E. Thornton, Oak Ridge National Laboratory

Chapter Authors

Louise Chini, University of Maryland

Amy E. East, US Geological Survey

John L. Field, Oak Ridge National Laboratory

Coeli M. Hoover, USDA Forest Service, Northern Research Station

Benjamin Poulter, National Aeronautics and Space Administration

Sasha C. Reed, US Geological Survey

Guiling Wang, University of Connecticut

Zhe Zhu, University of Connecticut

Technical Contributor

Joel Neimeyer, Neimeyer Consulting

Review Editor

Sara Bushey Ohrel, US Environmental Protection Agency

Cover Art

Kelly Curl

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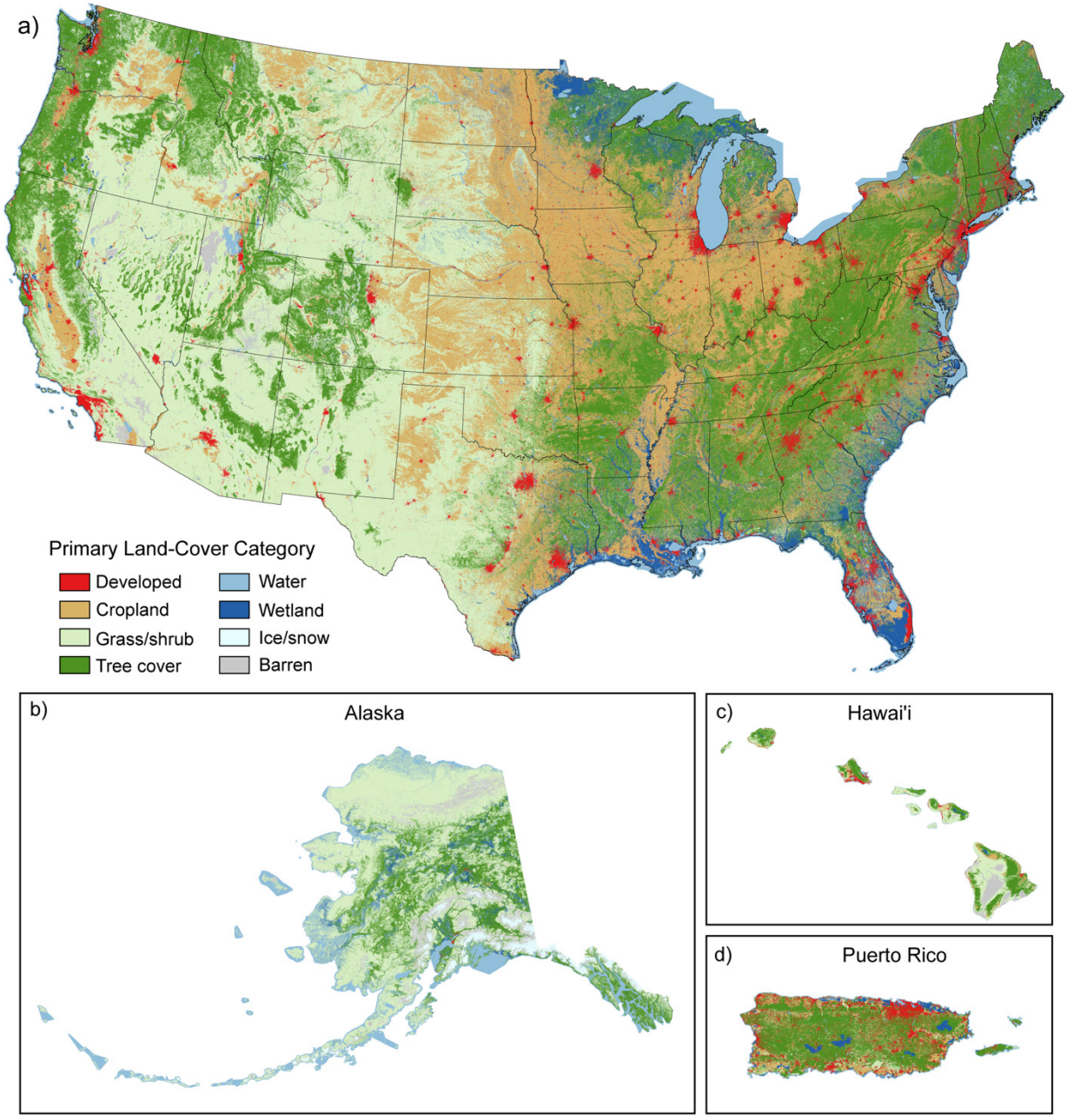
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Introduction

As Earth's climate changes, many critical aspects of the land system are at risk. "Land system" refers to both land cover (the physical organization of the land surface) and land use (the intentional ways humans interact with the land). Land system here also refers to the physical and ecological functions of land and changes in organization and function over time. Escalating concerns about how climate and global environmental change impact land systems and ecosystem sustainability have driven extensive research efforts to understand these complex interactions.[1,2,3,4,5] This chapter considers three broad categories describing the value of land systems to society and risks associated with climate change: 1) goods and services provided directly by land systems, 2) resilience of land systems in the face of disturbance, and 3) availability of options for future land use.

Analysis of these topics depends in part on reliable descriptions of historical and current land cover and land use. Satellite remote-sensing platforms and ground-based training data provide records of past and current land cover over the United States on a yearly basis (Figure 6.1).[6,7,8] Land-cover changes are caused by humans and ecosystem processes, with compounding effects from climate change, and are unevenly distributed in space and time. Some areas experience frequent land-cover changes from natural or human-caused disturbance (Figure 6.2), while other areas show progressive shifts in land cover, for example with the expansion of developed areas (Figure 6.3). While broad land-cover categories are relatively stable through time when aggregated to the national scale, varying by less than 10% from their 1985 values over the period 1985–2020, modest multidecadal changes within land-cover categories are still evident (Figure 6.4).

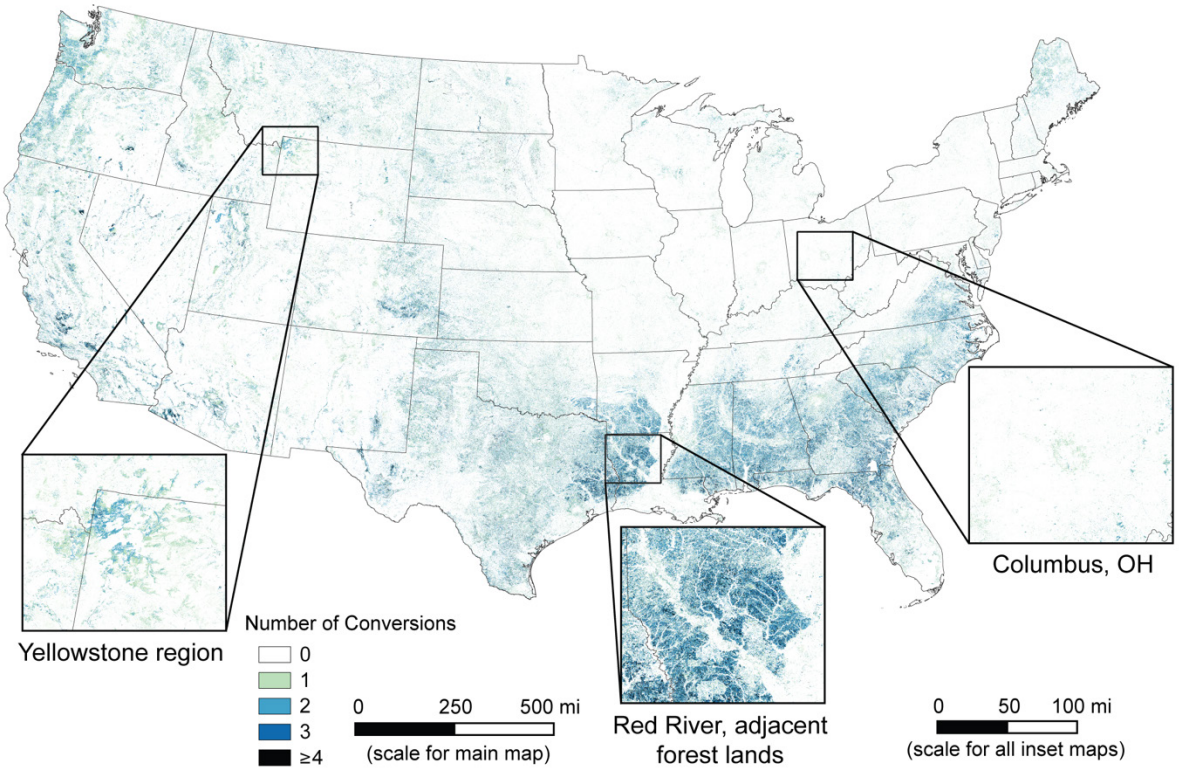
Present-Day Land Cover



The United States is characterized by complex spatial distributions of developed, managed, and natural land-cover types.

Figure 6.1. Data shown here are from different sources and for slightly differing time periods: (**a**) contiguous US from Land Change Monitoring, Assessment, and Projection [LCMAP] data for 2020; (**b**) Alaska from the National Land Cover Database for 2016; (**c**) Hawai'i from LCMAP for 2019; and (**d**) Puerto Rico from Coastal Change Analysis Program data for 2010. Developed land cover is clustered around urban centers, croplands dominate the central contiguous US, and managed and natural forests, grasslands, and shrublands are widely distributed. Figure credit: Oak Ridge National Laboratory and USGS.

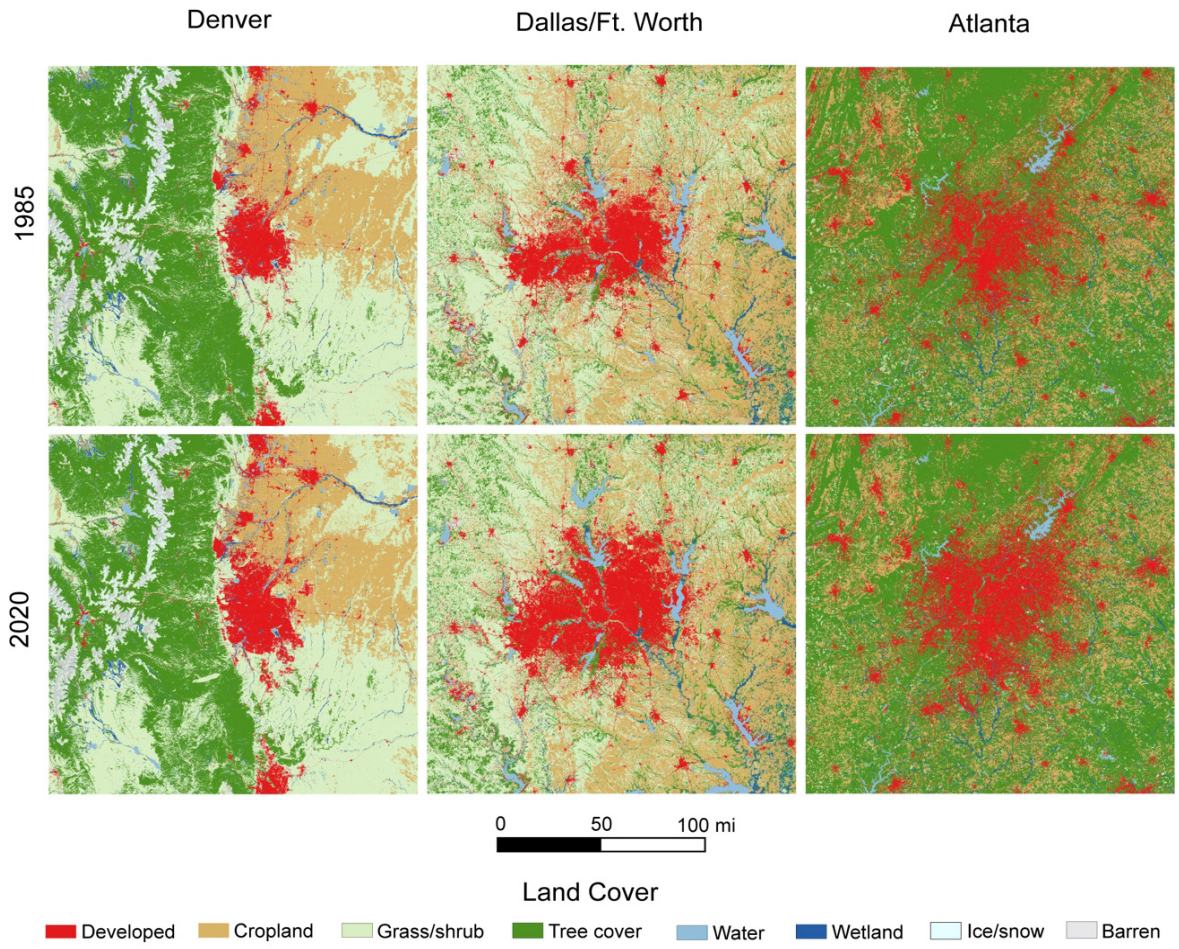
US Land-Cover Conversions, 1985–2020



Land-cover change can result from development, forest management, wildfire, and other causes.

Figure 6.2. Superimposed on the complex mosaic of land-cover types are patterns of land-cover change that vary among regions. The number of land-cover conversions is shown over the period 1985–2020. A conversion is defined for each LCMAP (Land Change Monitoring, Assessment, and Projection) 30 m x 30 m grid cell as a change between years from one primary land-cover category to another. The primary land-cover categories are as follows: developed, cropland, grass/shrub, tree cover, water, wetland, ice/snow, and barren. The frequency of conversion depends on multiple interacting factors. Development drives expansion of urban centers (e.g., around Columbus, Ohio). Forest management causes multiple land-cover conversions between forest and non-forest categories over decadal timescales while maintaining a consistent land use (e.g., around the Red River). Wildfire can cause large and long-lasting changes in land cover (e.g., in the Yellowstone region). The warming climate influences land-cover change by impacting development patterns, harvest recovery dynamics, and wildfire frequency and intensity. Figure credit: Oak Ridge National Laboratory and USGS.

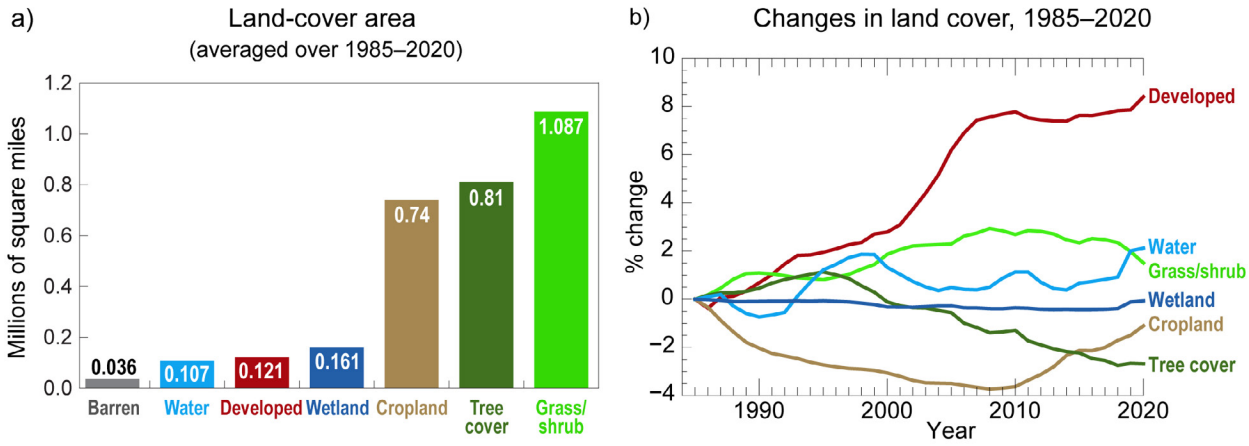
Expansion of Developed Land Cover



Increased development decreases natural and managed land cover.

Figure 6.3. Continuing expansion of development into vegetated land changes the array of climate-related risks to land system goods and services (KM 6.1), land system resilience (KM 6.2), and future land-use options (KM 6.3). Land-cover changes from 1985 to 2020 are shown for three urban areas: Denver, Dallas/Fort Worth, and Atlanta. Figure credit: Oak Ridge National Laboratory and USGS.

US Average Land Cover and Land-Cover Change



Developed land is increasing, while land with tree cover is on the decline.

Figure 6.4. Grassland, shrubland, cropland, and tree cover make up a large majority of the US land cover (**a**), and the area of these broad land-cover types changes relatively slowly over time when aggregated over the contiguous US. When expressed as a percentage change from the total land area for each cover type relative to values in 1985 (**b**), developed land has the largest increase through 2020. The area with tree cover has been declining since the mid-1990s, while the area of cropland declined through about 2010 and increased again through 2020. Figure credit: Oak Ridge National Laboratory and USGS.

Key Message 6.1

The Goods and Services Provided by Land Systems Are Threatened by Climate Change

Climate change has increased regional intensity and frequency of extreme rain, droughts, temperature highs, fires, and urban floods (*high confidence*), posing increased risks for roads and other infrastructure, agricultural production, forests, biodiversity, carbon sinks, and human health (*high confidence*). Climate-driven increases in wildfire extent and intensity are threatening the ability of some western forests to provide valued goods and services (*high confidence*). Climate change has disrupted the ways that people interact with the landscape for spiritual practices, recreation, and subsistence (*high confidence*).

Infrastructure, Public Safety, and the Built Environment

People expect land to provide a solid and permanent footing for infrastructure, public safety, and the built environment. Climate change threatens this in numerous ways, including increases in erosion, permafrost thaw, slope failure, fire, flooding, and shoreline retreat. Land-use changes themselves can interact with these climate impacts in complex ways (KM 6.2).

As sea levels rise, coastal infrastructure is increasingly exposed to risks of flooding and wave action from storm surges and nuisance flooding during high tides, with low-income coastal communities facing greater risks due to fewer resources for response (KMs 9.2, 23.1). The Atlantic and Gulf Coasts are particularly vulnerable to high tide flooding.[9] Decadal-scale variability in Great Lakes water levels drives shoreline erosion (KM 24.5). Increases in the magnitude and frequency of heavy rain in a warmer climate heighten the risk of damage from river flooding, especially where infrastructure for water storage, treatment, and

transfer becomes overwhelmed. Increased storm rainfall puts roads and buildings at greater risk of damage by landslides.[10] For example, Hurricane Maria, a Category 4 storm in 2017, caused substantial damage and fatalities in Puerto Rico, as well as more than 70,000 landslides.[11]

Warming of colder regions such as Alaska presents significant risks. Damage to roads and the Trans-Alaska Pipeline System is occurring due to ground destabilization as permafrost thaws.[12,13] As steep, rocky terrain warms and thaws, rockfalls can increase,[14] and as tidewater glaciers retreat, newly destabilized slopes in front of glaciers can collapse into water, causing potentially hazardous tsunamis.[15,16]

The USGS[17] provides emergency assessment of postfire debris-flow hazards (Focus on Western Wildfires). Fire and postfire debris flows increasingly threaten infrastructure and public safety as a warming climate and increased drought raise the risk of large, intense fires.[18,19,20,21] Notable among recent examples was the debris flow following the Thomas Fire in Southern California, which killed 23 people, damaged 558 structures, closed a major highway for 13 days, and caused more than $1.15 billion in damages (in 2022 dollars; Figure 6.5).[22,23] Risks to water supply and quality continue for years after a fire, as erosion washes excess sediment and pollutants downstream,[24] shortening the lifespan of water-storage reservoirs.[24,25,26] Sediment production is projected to double in one-third of western US watersheds by 2050 due to increased fire and extreme rain.[26]

Damage from Postfire Debris Flows



Postfire debris flows threaten public safety.

Figure 6.5. Photos show property destroyed by postfire debris flows in Montecito, California, caused by intense rain on January 9, 2018, falling on areas burned by the Thomas Fire in the previous month. Both contributing events—a large wildfire and extreme rain—are projected to become more frequent with climate change. Photo credits: Jason W. Kean, USGS.

The Southwest faces additional challenges to infrastructure and public health and safety from increased airborne dust,[27,28,29] which can carry human disease and result in traffic accidents.[30,31] Vegetation loss during drought can cause marginally stable land to transition to actively migrating sand dunes, some of which damage buildings and roads.[32,33]

Agriculture: Crops and Rangelands

Land provides essential services by supporting the production of food for people, feed for animals, and forage for wildlife. Climate change has led to increased extremes of both temperature and precipitation, with increased risks to crop yield (KM 11.2) and associated impacts on land-cover and land-use change (LCLUC). Crop yields in the US continue to increase but are subject to large year-to-year fluctuations driven by environmental stresses[34,35] and have become increasingly sensitive to water availability over the past two decades.[36] Yield loss associated with warming has resulted primarily from drought, with heat stress playing a secondary role.[37] Flooding also causes crop damage; during 1981–2016 in the US, inundation-induced yield loss was comparable in magnitude to that caused by extreme drought.[38]

In arid and semiarid lands of the Southwest, livestock overgrazing, oil and gas extraction, and off-road vehicle use amplify the effects of warming[39] by damaging vegetation and biological soil crusts,[40] further increasing dust production. The spread of invasive plants exacerbates this transition, leaving landscapes less adaptable to warming.[41] Water extraction by humans lowers water tables, stressing plants, drying lakebeds, and increasing dust production. These factors, together with the warming-induced drought, reduce the productivity and carrying capacity of US rangelands (KM 28.3).

Forests and Biodiversity

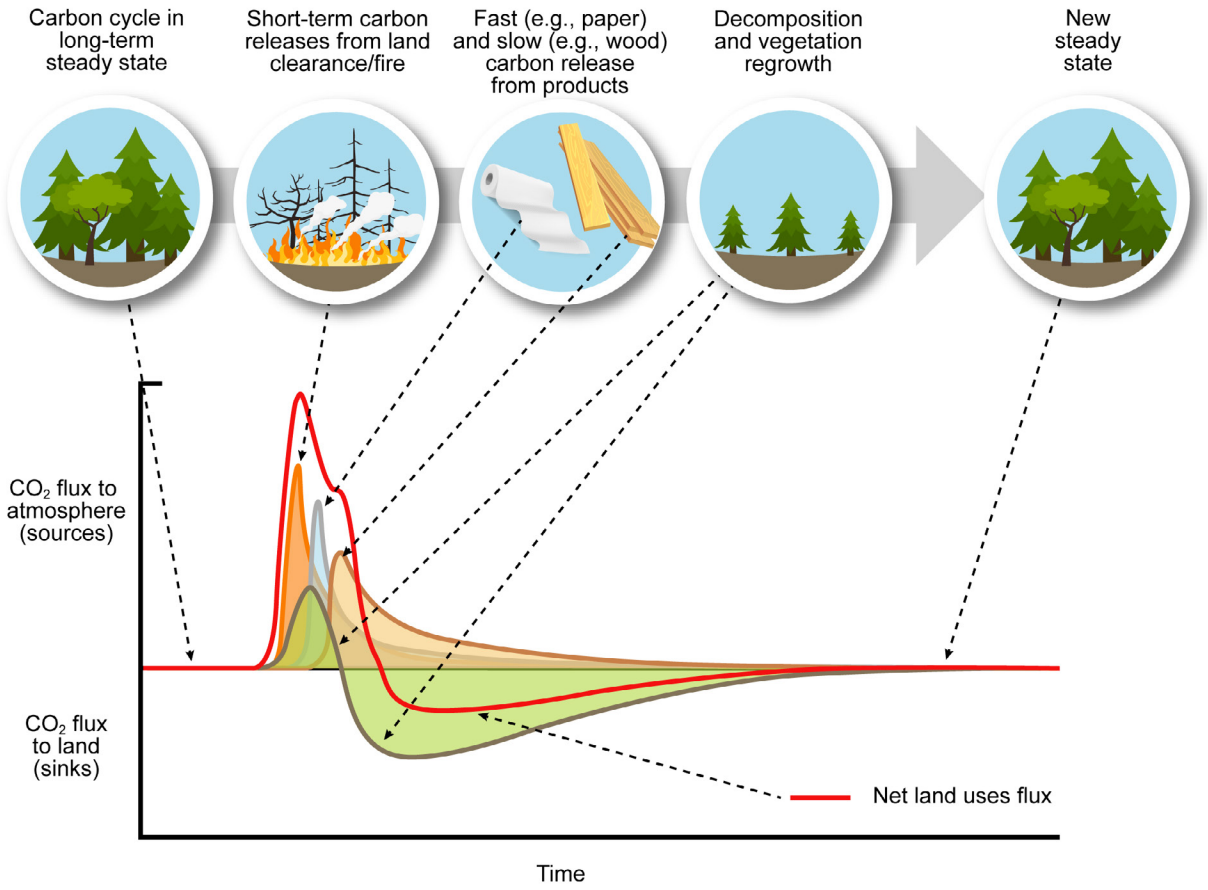
Forests provide critical value to society by supplying a wide range of wood products, protecting water quality, supporting biodiversity, and providing recreational opportunities and spiritual and cultural benefits. Forest land cover can reduce warming locally by providing increased evaporation and shade.[42] The effects of land-use change on forest goods and services, including the value of biodiversity, are still being explored.[43,44,45] In some cases, forest management can increase biodiversity and offset regional losses due to urbanization, but future losses of biodiversity due to climate change may be greater than reforestation offsets.[46]

Multiple interacting factors drive changes in goods and services from forest lands, including development, abandonment and expansion of agricultural land, and incentives for reforestation and conservation.[47] Mixed land uses such as agroforestry are expected to increase soil water infiltration compared to agriculture alone, providing protection against warming, drought, and soil erosion due to overland flow during extreme precipitation events.[48] Forest land-use transitions intended to mitigate climate change must be carefully assessed to prevent unintended consequences, such as net losses of carbon, biodiversity, habitat, soil quality, or other ecosystem services when converting mature forest to bioenergy crop cultivation (e.g., Harper et al. 2018[49]).

Natural and Managed Carbon Sinks

Land ecosystems provide an important service to society by sequestering a fraction of the carbon emitted to the atmosphere through fossil fuel combustion and land use. The net carbon balance at any location is the result of multiple simultaneous losses and gains related to plant growth and organic matter decomposition (KM 8.1), historical and current LCLUC, and climate conditions including atmospheric carbon dioxide (CO_2) concentration and local rates of nitrogen deposition (Figure 6.6).[50] Northern Hemisphere forests are important carbon sinks (KM 7.1).[51] Boreal and tropical forests are both globally important carbon sinks, and since 1992 the boreal forest sink has been increasing in importance relative to the tropical forest sink.[52] Other ecosystems, such as grasslands,[53] wetlands,[54] and some agricultural systems (KM 11.1)[55] also contribute to the carbon sink, with complex and uncertain interactions with management actions.

Carbon Flux Response to Land-Cover and Land-Use Change



Changes in land cover and land use affect the fluxes of carbon taken up on land or released into the atmosphere, with impacts on these fluxes lasting for decades to centuries.

Figure 6.6. Land-cover or land-use changes can trigger complex sequences of carbon release and uptake. The example shown here illustrates a single idealized land-use event and the multiple impacts of such an event on carbon release and uptake fluxes. Net carbon flux from land use (red line) depends on time since disturbance, with climate change impacting all the component fluxes. Component fluxes include immediate losses from land clearance and fire (orange line), fast release of carbon from decomposition of forest products such as paper (blue-gray line), slow release from forest products such as lumber (brown line), and initial decomposition of litter and soil organic matter followed by carbon uptake during regrowth (dark gray line). The processes represented here typically span multiple decades to a century or more. In this illustration the net carbon flux (red line) eventually returns to zero, indicating that the influence of a single event has a finite period of impact on fluxes. During this period of impact, accumulated carbon losses (summed area of the red line above the zero flux level) can differ from accumulated carbon gains (summed area of the red line below the zero flux level), resulting in new steady states with either more or less total carbon storage than before the land-use event. Multiple events such as this can occur over time at a single location and can overlap each other in time, leading to even more complex patterns of fluxes. Figure credit: Oak Ridge National Laboratory.

While highly variable from year to year, the fraction of emissions taken up by land ecosystems has remained relatively stable on decadal timescales (Box 7.2). Recent evidence suggests that plant response to increasing atmospheric CO_2 is the dominant factor driving the land carbon sink at global scales.[56,57] A significant part of the land sink is also attributed to recovery following natural disturbances and legacy effects of past LCLUC.[58,59,60,61]

Intrinsic Value

Impacts of climate change are transforming landscapes in ways considered intrinsically detrimental. Communities with especially strong ties to place and local ecosystems, including but not limited to Tribal and Indigenous groups, may suffer declining cultural and spiritual connections with the land through these changes (KM 15.2),[62] such as through the drying of formerly perennial springs and streams that have spiritual significance[63] or through reduced opportunities for traditional harvesting of plants that decline as environmental conditions change. In central and northern Alaska, traditional methods of hunting on sea ice have become less feasible, and destabilization of thawing permafrost jeopardizes long-occupied communities (KM 29.3).[64,65] Subsistence and recreational fishing are reduced by ecosystem changes, some of which are climate driven and will worsen with additional warming;[66] for example, decreased salmon abundance has profound negative effects on many Tribes in the Northwest (KM 27.1).[67] Other recreational land uses are limited by the changing seasonality of river flows, loss of ice and snow, and loss of access to areas recently burned.

Key Message 6.2

Changes in Climate and Land Use Affect Land-System Resilience

Changes in climate and land use affect the resilience of land ecosystems and thus the fate of the services they provide (*high confidence*); for example, increasing drought reduces the ability of forests to store carbon. Climate and land-use change interact, and these interactions present challenges as well as opportunities for maintaining ecosystem resilience (*high confidence*).

The Value of Resilience

Ecosystem resilience—defined here as the capacity of a land system to respond to disturbance by resisting damage and/or recovering quickly, maintaining its essential structure and function—determines the persistence of services amid LCLUC. Disturbance is defined here as any discrete event (e.g., fire, flooding, drought, wind, geological hazard, pathogen, insect infestation, etc.) that occurs outside the range of natural variability (e.g., vegetation phenology, climate interannual variability, etc.) of the land system.[68] Management also impacts land systems, with the potential to both increase or decrease resilience. Resilience enables natural and built systems to maintain the continued delivery of goods and services in the face of changes. Climate change is affecting ecosystem resilience, triggering responses such as shifted distribution of species and reduced biodiversity (KM 8.2),[69,70] changed timing of biological processes,[71,72] altered success of existing land uses,[73,74] and lowered ability of systems to resist and recover from land-use activities and natural disturbance.[75] Ecosystems in the US have experienced increases in average temperature and extreme heat,[76] increased drought,[77] and increased intensity and frequency of extreme precipitation.[78,79] Changes in precipitation characteristics and warming have driven an increase in aridity in much of the United States,[80,81] with lasting impacts on ecosystems.[82] Land use and management affect ecosystem resilience and interact with climate change to determine the structure and function of the land system (KM 20.3).[83,84] The fact that human decisions can influence resilience provides opportunities for climate mitigation (Ch. 31) and adaptation (KM 6.3; Ch. 32) and is a foundation for nature-based solutions to climate change,[85] as well as an opportunity to improve resilience through management actions informed by Indigenous Knowledge (KM 16.2).[86]

Interactions Between Climate Change and the Land System and Effects on Resilience

Climate change and land use individually and interactively affect land systems, the services they provide to humans, and the resilience of ecosystems. Climate change alters landscape characteristics and management outcomes, which drive changes in land use and/or land cover (Figure 6.7). Land use itself impacts the land system, with potential to both increase and decrease resilience. Land use and land cover help determine climate via effects on carbon, water, and energy exchange with the atmosphere.

Climate change affects ecosystem resilience, structure, and function. For example, tree mortality events have resulted from drought and/or high temperatures in the temperate and boreal forests of western North America,[87,88] and widespread death of many tree species has been linked to climate change through wildfire and insect attack.[89,90] Warming-induced drought is causing widespread mortality of forests in the Southwest US.[91] Increased tree mortality and impaired regeneration decrease the resilience of forests (KM 7.1).[92,93]

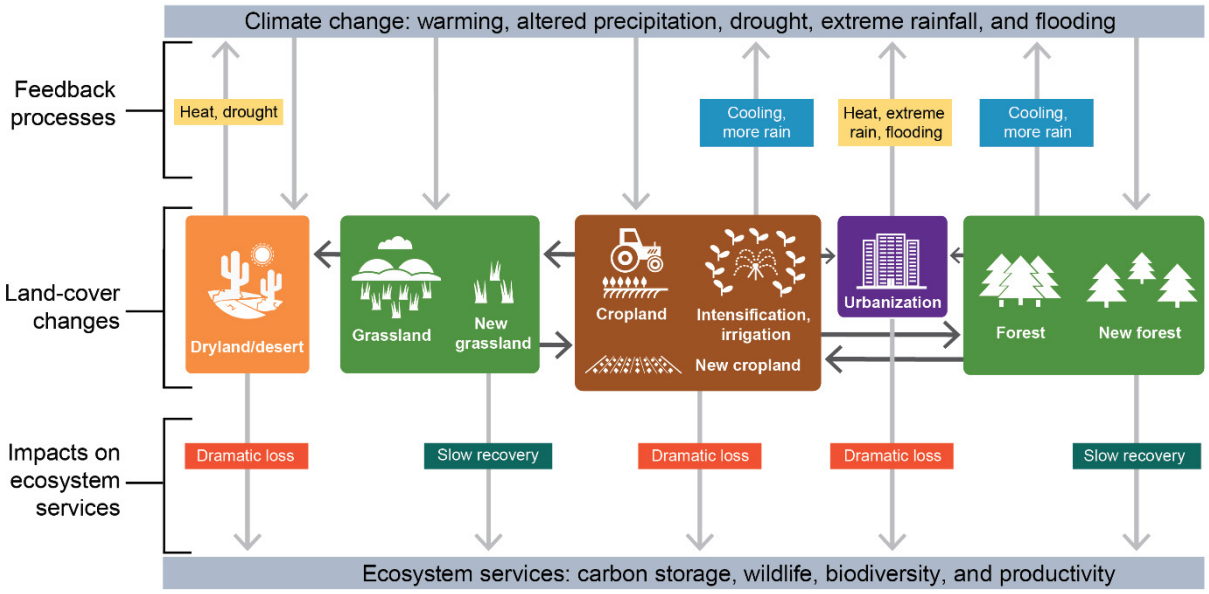
Increases in average temperature and altered precipitation patterns cause changes in species composition,[92,93] such as encroachment of shrubs into grasslands[94] and invasion by exotic grasses into rangelands, drylands, and forests.[41,95] Exotic grass invasion increases fuel loads and the ability of fire to move across the landscape, often resulting in large increases in fire risk.[41,96,97] By reducing fuel moisture, hotter and drier climates lengthen the wildfire season and lead to larger, more severe fires.[20,21] Increased wildfire frequency and severity can result in the loss of soil organic carbon through combustion[98] and postfire erosion.[24] In boreal systems, increased fire frequency may lead to changes in forest type,[99] while streamflow changes and permafrost thaw may trigger transition from peatland to forest.[100,101] Interactions between fire, climate change, and human development are multifaceted and include not only warming-induced increases in wildfire but also management actions to reduce wildfire fuel, the effects of fire on human populations, postfire recovery, and fire-induced changes in forest type (KM 8.1). Drought, wildfire, and unsustainable land-use practices cause land to lose productivity, which may trigger desertification in arid and semiarid regions.

Changes in land cover influence local and regional climate through both biogeochemical and biophysical pathways. The biogeochemical effects of vegetation loss, including both immediate CO_2 emissions and missed capacity for carbon sequestration (KM 6.1), have a warming impact at the planetary scale.[102] Vegetation loss causes immediate changes to local and regional climate through biophysical effects (e.g., Jiang et al. 2021;[103] Wang et al. 2016[104]), including exposed ground or snow (cooling the surface by reflecting more sunlight), reduced evapotranspiration (warming the surface and reducing moisture supply for rainfall), and a smoother surface (warming the surface by reducing heat loss to the atmosphere). The net impact of land-cover change on local climate depends on season, background climate, and vegetation type. Across the United States, forest disturbance or forest loss during the 2000s and 2010s caused a net local warming at both evergreen and deciduous sites in arid/semiarid, tropical, temperate, and boreal zones.[105,106] This occurred because warming from the loss of transpiration more than compensated for the cooling effects of the more reflective land surface following forest loss; exceptions were found during boreal winter at high latitudes where strong cooling resulted from high albedo of exposed snow.[105,107] Similarly, climate over forests is cooler than the surrounding croplands and urban areas, and the increase of forest cover following agricultural abandonment during 1920–1990 is connected to the observed cooling trend in the Southeast US.[108]

Indirect interactions also have impacts on US ecosystem resilience.[1,109] Land-use decisions that consider the interactions of climate change and management can maintain and promote ecosystem resilience.[83,110] For example, the thinning of some western forests that are experiencing drought increases the resilience of the forests to future trends of warming and drying.[111]

Changes in climate and land use offer opportunities for mitigation and adaptation, such as post-disturbance restoration of lands using climate-adapted species, which could increase biodiversity and resilience to climate change.[112] Increasing land-based carbon storage may be achieved by shifts in land management (KM 6.3), for example by afforestation (Ch. 7), altered grazing practices (Ch. 11),[53] modified crop management (Ch. 11), conserved agricultural lands,[113] active restoration of disturbed lands,[114] and the use of prescribed fire to avoid wildfire.[115]

Land, Climate Change, and Ecosystem Resilience



This figure shows the primary land-use and land-cover changes, their interactions with climate, and impact on ecosystems.

Figure 6.7. Land-use and land-cover changes interact with climate change, leading to lasting impacts on ecosystem services and resilience. Black arrows represent land conversions, and gray arrows represent impact or feedback processes supported by existing literature. Figure credit: University of Connecticut, USDA Forest Service, USGS, and Oak Ridge National Laboratory.

Land System Resilience Risks Associated with Increasing Development

Among all classes of land-cover change in the contiguous United States between 1985 and 2016, the largest net change in any class was an estimated gain of 50,660 square miles (131,209 km^2) of developed lands, at an average rate of 1,634 square miles (4,233 km^2) per year, primarily at the expense of forest and agricultural land,[116] a trend that continues to the present (Figure 6.4). Urban heat island effects exacerbate the impacts of warming on heat hazards, which disproportionately harm low-income communities (KM 12.2; Figure 12.6; App. 4). Warming-induced increases in precipitation extremes lead to higher flash flood risks, with especially devastating effects in urban regions where impervious surfaces cannot absorb rainwater. Although widespread increases in intense rain are evident,[117] river flooding trends are not consistently apparent across the US at present (KM 4.2);[118] however, in urbanized basins, as urban development expands, the size of flood peaks increases.[117,119,120] A resilient urban infrastructure, therefore, must be able to accommodate increased runoff from extreme storms (KM 12.2). Urbanization, through both urban land cover and increases in human-caused fine particulate matter, can alter atmospheric convection and precipitation, leading to stronger storms and more intense precipitation.[121,122,123,124] Urban heat islands reduce low clouds,

which can increase plant water stress and possibly play a role in increasing wildfire risk, particularly in the wildland–urban interface.[125,126]

The adverse effects of urbanization on climate and ecosystems can be partly alleviated through sustainable practices designed to improve urban resilience. Urban greenspace (e.g., urban forest, farming, gardening) can mitigate the urban heat island effects and flooding risks[127,128,129] with varying degrees of effectiveness. While urban vegetation sequesters carbon during the growing season, the annual net carbon flux is uncertain.[130,131,132] Additionally, urban farming brings food security benefits, with yields comparable to conventional agricultural yields.[133]

Increasing energy demand, combined with new extraction technologies, has resulted in an average of 50,000 new oil and gas wells established per year throughout central North America since 2000.[134] Infrastructure for horizontal drilling and high-volume hydraulic fracturing has transformed millions of acres into industrialized landscapes, with reductions in ecosystem resilience, biodiversity, and the land carbon sink (e.g., Allred et al. 2015[134]). Reclamation of wells could become less successful with climate change.[135] The efficacy and resilience of renewable energy systems are expected to be affected by climate change in ways that will vary with generation type and location [136] and may strain the energy system (KMs 5.1, 5.2, 5.3).

Land System Resilience Risks Associated with Changes in Agriculture

After declining for multiple decades, cropland area in the United States increased at a rate of approximately 1,500 square miles (approximately 4,000 km^2) per year during 2008–2016 (Figure 6.4b),[137] attributable to increased domestic demand for corn ethanol and global demand for agricultural commodities as well as changes to conservation and crop insurance programs, interest rates, and possibly climate change–driven crop migration.[138,139] New croplands tend to occupy areas with marginal biophysical characteristics (e.g., erosive soils, nutrient deficiency, climatic stress) but displace grasslands and conservation easements that are higher-quality wildlife habitat than the remaining natural lands.[137] Expansion of agricultural area in the north-central United States has led to fragmentation of the remaining grassland, which limits the dispersal and population of native species (e.g., Wimberly et al. 2018[140]) and is expected to reduce ecosystem resilience. Conversion of grassland to cropland also contributes to carbon emissions from loss of soil organic carbon (KM 11.1).[141] The recovery of plant biodiversity, productivity, and soil carbon following agricultural abandonment is slow,[142] but the potential recovery of carbon in lands released from agricultural use is substantial, as has been shown by the large soil carbon gains made in land under the Conservation Reserve Program (KM 11.1).[113] Soil carbon increases, as well as increases in other ecosystem services, can be accelerated through activities such as deliberate revegetation with woody and herbaceous perennials.[143]

Agricultural extensification influences precipitation, with the direction of change depending on the region and the type of natural land cover prior to its conversion to cropland. For example, replacing grassland with cropland over the Great Plains can cause summer precipitation to increase.[144] Studies suggest that, in addition to increased area, intensification and irrigation are major causes of the observed increases in precipitation and decreases in temperature in the central US and Midwest[145,146,147,148]—changes that provide potentially more favorable conditions for crops and surrounding ecosystems. Land conversion to cropland without intensification was not associated with the observed cooling.[146]

Key Message 6.3

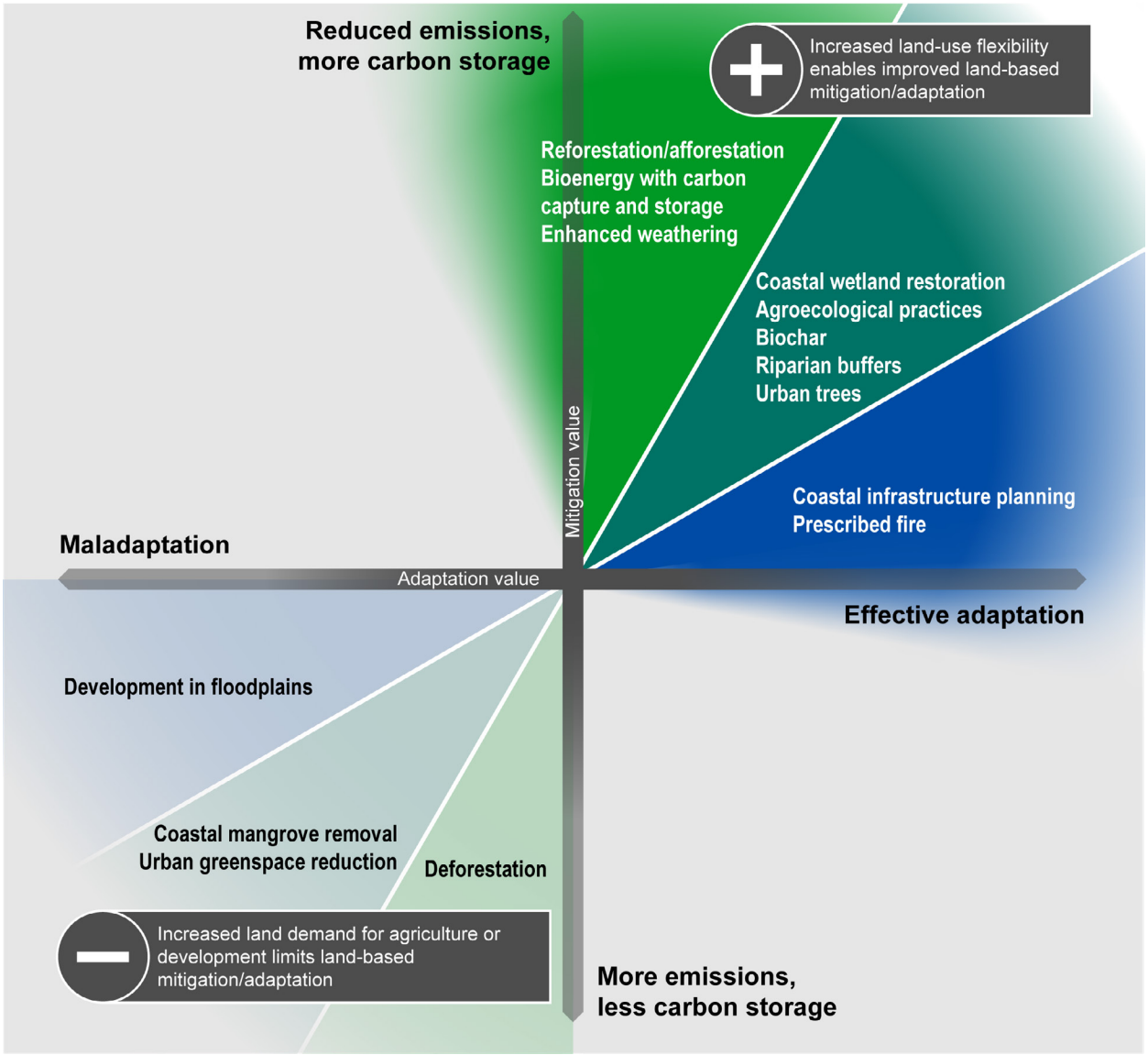
Mitigation and Adaptation Priorities Will Increasingly Constrain Future Land-Use Options

The future of land use in the United States will depend on how energy and agricultural technology evolves, how the climate changes, and the degree to which we prioritize climate mitigation and adaptation in land-use decisions (*high confidence*). US cropland area had been declining but has rebounded somewhat over the last 1–2 decades (*high confidence*). Future cropland needs will depend on uncertain factors such as agricultural technology improvements, dietary shifts, and climate change impacts (*medium confidence*). Decarbonization will require a continued expansion of solar and wind energy generation and transmission infrastructure (*very likely*, *high confidence*) and may involve large land-use changes toward land-based mitigation measures, including reforestation, other natural climate solutions, and bioenergy crops (*low confidence*).

Future Land-Use Scenarios

People value the ability to choose among multiple land-use options, although the ability to make these choices is not always experienced equitably across society (KM 20.3). There are increasing and competing demands for future land-use changes to support agriculture, housing, and infrastructure; to contribute to climate change mitigation and adaptation; and to conserve and possibly restore natural lands for biodiversity, resilience, and spiritual or recreational use. Scenario analysis is used to explore different climate mitigation "storylines," known as Shared Socioeconomic Pathways (SSPs; Table 3 in Guide to the Report), for how global land use, energy systems, and greenhouse gas emissions might evolve together under a set of standardized background driving forces such as changes in population, technology, and governance.[149,150] Land-use representation within the range of SSPs includes differences in land-use regulation, land productivity, trade, land-based mitigation and adaptation (Figure 6.8), and food/diet choices, along with a corresponding range of land-use trends that result from these drivers (Figure 6.9).

Mitigation and Adaptation Value of Future Land-Use Choices



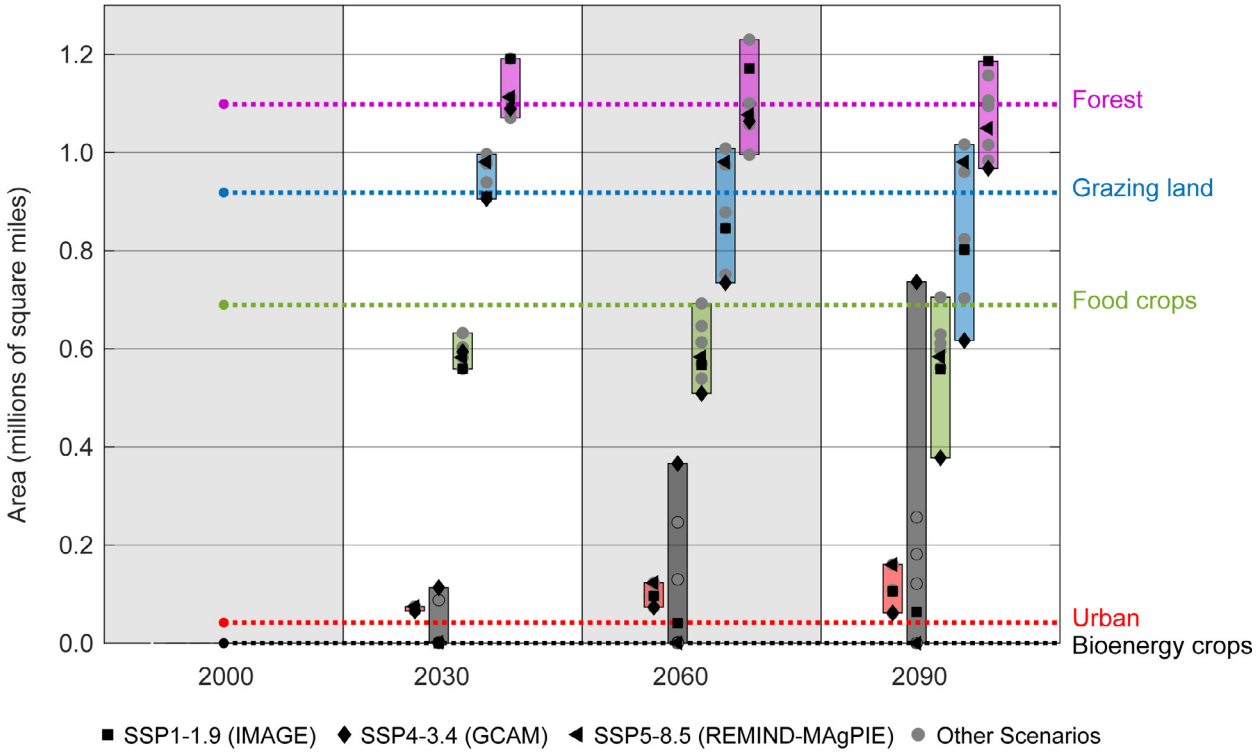
Future land-use choices have implications for climate mitigation and adaptation.

Figure 6.8. Future land-use choices can contribute to mitigating global climate change by reducing emissions or storing carbon (green), help individuals or communities adapt to the effects of global change (blue), or simultaneously support both mitigation and adaptation (green-blue), as shown in the upper-right quadrant. Flexibility in land use for mitigation and adaptation depends on background factors, including agricultural technology improvement, income growth, food waste reduction, and international cooperation. Alternately, indiscriminate land use change can lead to additional carbon emissions or maladaptation (lower-left quadrant). Many of these land-use choices are discussed elsewhere, including Key Messages 7.3 (forest adaptation), 9.3 (coastal adaptation), 11.1 (agricultural adaptation), and 12.3 (urban trees), as well as Box 32.2 (carbon dioxide removal). Figure credit: NASA, University of Maryland, and Oak Ridge National Laboratory.

Future land uses in the United States have been explored under several SSPs and at multiple spatial scales.[151] Future land use within the SSPs (Figure 6.9) is projected to involve substantial departures from historic trends (Figure 6.4), with determinants of change and resulting land-use patterns varying spatially and with time, based on multiple drivers including land management, demographic change, and ecological shifts (e.g., Richter and Bixler 2022 [152]). Many scenarios assume continued agricultural productivity

increases, allowing the total area of cropland for food production to remain stable or decline despite the increasing global population.[150] Future land-use changes that limit global warming include reductions in grazing land associated with lower-animal-calorie diets and climate mitigation via reforestation or forest expansion. In addition, to offset fossil fuel use in other sectors, an often-dramatic expansion of bioenergy crops (producing nonedible plant material) is included in many scenarios. Large increases in urban area and reductions in forest area often accompany scenarios that involve greater levels of climate change.[153] Although these scenarios are useful for exploring different possible land-use futures at the aggregate scale, they do not quantify the likelihood of different land-use changes.

Scenario-Based Future Land-Use Trends



Future land-use scenarios describe a wide range of possible land-use changes in the United States.

Figure 6.9. Future land use in the 50 US states across eight different Shared Socioeconomic Pathways (SSPs) depicts increases in urban area, stability or decline in food crop area, and mixed outcomes for remaining land-use types, with large divergence among scenarios. (Data for the US-Affiliated Pacific Islands and US Caribbean are not included due to the spatial resolution of the underlying data source.) Colored bars show the range of land-use areas across all scenarios, and dashed lines indicate year 2000 values for comparison. Black symbols illustrate results for select scenarios of low emissions and high reforestation (SSP1-1.9 from the IMAGE model), moderate emissions with large nonedible bioenergy crop growth (SSP4-3.4 from the GCAM model), and high emissions (SSP5-8.5 from the REMIND-MAgPIE model), while gray symbols represent remaining scenarios. The large expansion of bioenergy crops is often taken from natural grasslands, which are not represented in this figure. Figure credit: University of Maryland, Oak Ridge National Laboratory, and NASA.

Future Agricultural Land Use

Flexibility in future land-use decision-making may be limited by agricultural land needs. Climate change is estimated to be slowing the rate of crop yield increases globally;[154,155] future land use will depend on the ability of the agricultural sector to adapt. Modeling results indicate that climate change–driven regional crop disruptions may emerge within 2–3 decades,[156] although such disruptions would be minimized with the adoption of adaptation and intensification measures such as supplemental irrigation and updated crop varieties.[157,158] There is also evidence of agricultural system adaptation through migration of crop cultivation ranges into more favorable climates in the United States and globally.[159]

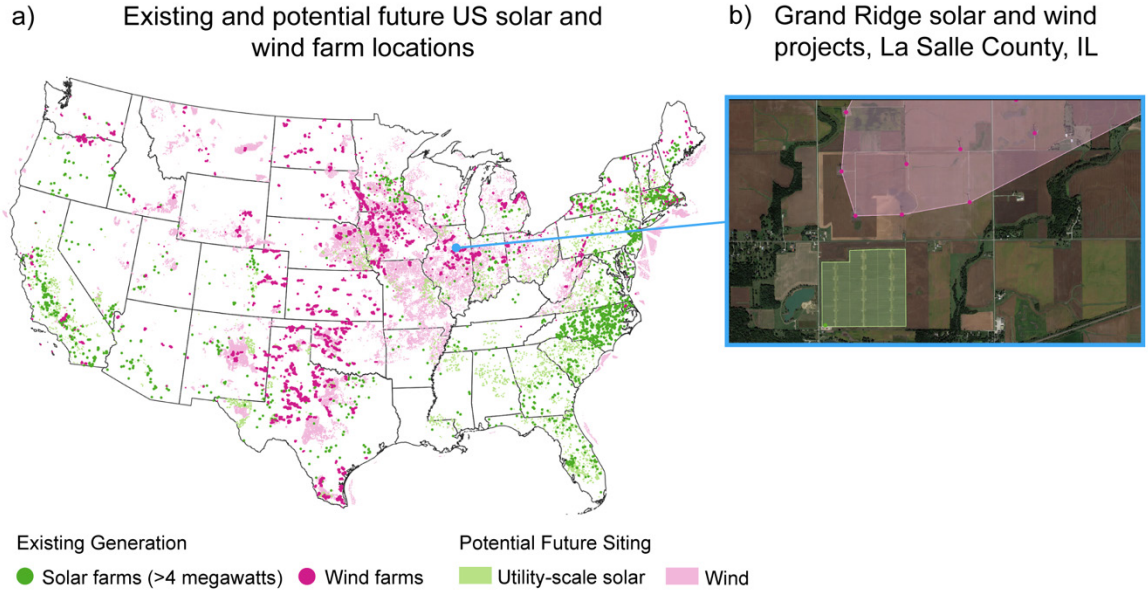
Individual farmers and landowners experience these changes in the context of increased variability in yields and income. As much as one-fifth of recent US crop insurance losses can be attributed to climate change.[160] Over time, adverse climate trends might affect the financial viability of current cropping practices and create pressure for individual producers to adopt adaptation practices (e.g., earlier planting dates, new crop varieties, modified tillage practices)[161] or switch crops. Such impacts will disproportionately affect small rural landholders (KM 11.3). Some regions are expected to see opportunities for new cropping systems[159,162] or for increasing the frequency of cropping on a given field.[163]

Future agricultural land requirements and associated climate feedbacks are sensitive to dietary choices and food waste.[164] American diets are high in meat consumption, a land-intensive food source, and universal adoption of USDA dietary guidelines would lead to a net reduction in the total biophysical land requirement for US agriculture.[165] Shifting toward diets even lower in animal products—potentially via novel plant-based meat substitutes[166]—could spare additional land and enable restoration of natural ecosystems.[167,168] US agricultural land futures could also be influenced by a continuation of the reduced household food waste observed during the COVID-19 period.[169,170]

Future Land Use for Mitigation

Mitigation scenarios that limit global warming to 1.5° or 2°C (2.7° or 3.6°F) above preindustrial levels imply large expansions of renewable energy production, electricity transmission, and land-based carbon mitigation (Ch. 32).[171] In scenarios of net-zero emissions by 2050, wind turbines may be visible across more than 130 million acres, an area greater than Colorado and Wyoming combined (Figure 6.10).[172] However, individual wind turbines have a small physical footprint, and can be sited in areas of intensive agriculture (Figure 6.11).[173] While solar farms are more land-intensive than wind- and fossil-derived electricity sources,[174] it may be possible to integrate them into agricultural landscapes in ways that preserve or even enhance agricultural production.[175] Decarbonizing energy systems will require a multifold expansion in global production of key metals and minerals,[176] although proposals to build new mines or expand existing mines in the United States have often faced intense local opposition.[177]

Possible Future Wind and Solar Power Siting



Reaching net-zero emissions will require many new wind and solar projects across the US.

Figure 6.10. Decarbonization will require an expanded physical and visual footprint of renewable power generation. Panel (**a**) shows current and possible future siting of wind and solar generation under a scenario that reaches net-zero emissions by 2050.[172] Panel (**b**) is a zoomed in view of the existing Grand Ridge wind and solar projects in La Salle County, Illinois and possible future siting zones. Green and pink dots show locations of existing solar and wind generation, respectively. Light green and light pink shading shows potential future siting of utility-scale solar and wind. Figure credit: Oak Ridge National Laboratory, with panel (b) background imagery © 2023 Landsat/Copernicus, Maxar Technologies, USDA/FPAC/GEO, map data © 2023 Google.

Wind Power in Agricultural Landscapes



Renewable energy generation can be sited in ways that minimize agricultural disruption.

Figure 6.11. While wind turbines may be visible over an area of more than 130 million acres under some net-zero scenarios,[172] the actual amount of land they physically occupy is much smaller. Photo credit: franckreporter/E+ via Getty Images.

The purposeful use of vegetation to capture or store additional carbon is one of the largest but most uncertain elements in future land-use projections. Many scenarios rely on land-based mitigation measures,[178] including land-intensive reforestation or carbon-negative bioenergy production to achieve carbon dioxide removal (CDR) from the atmosphere,[172,179,180] often implying unprecedented rates of land-use change.[181] Bioenergy is the most land-intensive form of renewable energy,[174] although it is valued in integrated assessment models for providing fuels for long-haul aviation and freight transport in addition to CDR (KM 32.3). Future bioenergy expansion may rely on dedicated cellulosic biomass crops cultivated on low-value land to minimize conflicts with existing agricultural production,[182,183] with positive or negative effects on ecosystem carbon storage depending on previous land use.[184]

Existing experience with land-based mitigation measures is limited, and the efficacy of forest carbon offsets, agricultural soil carbon enhancement, and first-generation biofuel programs remains controversial.[185,186,187,188] Most of the limited CDR achieved to date has come from forest restoration and management, and current CDR deployment plans fall far short of the scale envisioned in many decarbonization scenarios.[189] In the

absence of such land-based mitigation measures, limiting global warming to below 1.5°C (2.7°F) will require even more aggressive emissions reductions[190] or breakthroughs in competing technologies such as direct air capture of CO_2.[191]

These mitigation trends imply new opportunities for landowners to generate additional revenues from leasing land for renewable energy generation or transmission, from government-run conservation payment programs, or from private carbon markets. However, these new opportunities also carry risks of conflict around conservation and the best use of public lands.

Broader Impacts of Land-Use Choices

Future land-use choices also include adaptations to climate change such as locating infrastructure away from potential hazards, strengthening natural ecosystems as buffers to climate extremes (e.g., coastal forests and wetlands), and planting trees in urban areas to reduce heat stress.[192] Many of these activities have mitigation co-benefits (e.g., urban trees also store carbon).[193] Efforts to reduce land use–driven habitat fragmentation are also expected to decrease the risks of disease transmission from animals or insects to humans, as well as pandemics.[194,195,196] All components of the food supply system are expected to be impacted by future land-use choices and climate change,[194] which will be felt unequally across society (KM 11.2). Land-use planning in the United States will be determined by many decision-makers, including land managers at federal, state, and local levels, as well as private and Tribal landowners, and achieving consensus over future land-use decisions is expected to be challenging.[197]

Traceable Accounts

Process Description

The chapter lead (CL) and coordinating lead author (CLA) developed a list of relevant topics and the expertise needed to represent those topics in the assessment process. The CL and CLA reviewed a list of nominated authors, which included information about affiliation and expertise. The CL and CLA identified potential chapter authors from that list based on their knowledge of the field, their expertise in the topical areas, and their contribution to the diversity of the author team in terms of affiliations, gender, and race. Invitations were sent and updated as necessary to adequately cover the needed expertise.

All meetings of the author team were virtual, except for the all-author meeting held in Washington, DC, in April 2023. Consensus was built during weekly meetings of the full author team, with candidate content developed by author sub-teams through additional weekly meetings. All authors participated in developing and conducting a public stakeholder engagement workshop, and all authors participated in reviewing and responding to public comments.

For development of candidate text for each Key Message, the authors discussed the key topics that should be addressed based on their assessment of the literature, expert knowledge, and input from agency and stakeholder meetings. The authors then assigned topics according to expertise and performed a literature review to evaluate and synthesize information regarding land use and land-cover change, climate change, and related ecosystem controls. Based on this review, they developed Key Messages, central points, and examples to communicate the issues, challenges, and opportunities related to land system goods and services, land system resilience, and future land-use options.

Key Message 6.1

The Goods and Services Provided by Land Systems Are Threatened by Climate Change

Description of Evidence Base

Land-cover and land-use datasets for the US are detailed and reliable when considering a relatively small number of land-cover types and land-cover or land-use transitions, although the best available data for different regions (contiguous US, Alaska, Hawai'i, and Puerto Rico) cover slightly different time periods and use different though related methods.

There is consensus that more extreme rain will cause more landslides in a warmer climate, but the spatial distribution of anticipated future effects has not been resolved with much certainty; Gariano and Guzzetti (2016)[10] provided a synthesis of many studies that, in total, support these interpretations. Some individual mass-movement events have been attributed directly to climate change, but many landslides are caused more directly by factors without a clear link to a warming climate, such as slope oversteepening (by human construction) or local soil, bedrock, and hydrologic conditions. A broad literature base supports these inferences. The link between climate and slope-failure hazards, including the characteristics of rainfall, terrain, and burn severity that contribute to postfire debris flows (e.g., Kean et al. 2019[22]), is a rapidly growing research area.

The literature examining agricultural land practice and connections to climate change is broad and deep, covering many cropping and forestry practices in many regions across the US. There is a tendency for studies to focus more on small regions than on broad spatial patterns.

There is a long history of research into the connections between forest land cover and biodiversity, and this assessment drew on an extensive body of literature. These systems are complex, and the literature examines these connections from many perspectives.

While the topic of natural and managed carbon sinks on land is addressed by a large body of research, predictive understanding of interactions of the land carbon sink with land-use and land-cover change under a changing climate is still evolving (e.g., Zhu et al. 2018[61]).

Major Uncertainties and Research Gaps

Land-use and land-cover datasets with good temporal coverage and detailed spatial information are still lacking or highly uncertain for high-latitude regions such as Alaska. Additional observations and synthesis of ground-based and remotely sensed data would be required to fill these gaps.

Geographic variation in the two-way interactions between climate change and agricultural practice points to gaps in understanding of the detailed mechanisms connecting agricultural practices to long-term climate variation.

Relationships between agricultural practice, forestry practice, and climate change in mixed-management agroforestry systems have received less attention than traditional cropping or forestry practices. To the extent that strong mitigation measures place higher demand on mixed-use systems for both production and carbon sequestration, additional effort would be required to fill these research gaps.

Comprehensive assessment of the many component fluxes and processes contributing to net greenhouse gas fluxes due to land-use and land-cover change is still an important gap at scales larger than a few tens of square miles. Regional and continental-scale studies continue to rely on sparse observations and relatively simple assumptions about how different disturbance types, frequencies, and intensities interact with ecological communities of vegetation and soil biota to drive long-term net fluxes between land and atmosphere.

Description of Confidence and Likelihood

Based on strong and abundant empirical evidence, there is *high confidence* that climate change is increasing the regional intensity and frequency of extreme events, including rain, droughts, temperature highs, and fire. There is likewise a strong theoretical foundation for the attribution of these effects to human-caused climate change at present and further evidence that these effects will increase in the future as greenhouse gas concentrations rise. The empirical and theoretical basis for attributing changes in flood frequency and intensity is also robust, but not as strong as for extreme precipitation, droughts, and fire.[21,77] Based on abundant documentation, there is *high confidence* that these changes in weather and climate extremes cause risks to infrastructure, agriculture, ecosystems, and human health.

Broad empirical and theoretical understanding provides *high confidence* that wildfire is a major risk to the permanence of land carbon sinks, especially in woody ecosystems that have the potential to transition to savanna or grassland under increased fire frequency and/or severity. Other aspects of the net storage of carbon on land due to disturbances such as rotational forest harvest, windthrow, insect damage, and shifting agriculture are commonly identified as significant sources of uncertainty in estimating global or regional-scale carbon budgets.

Based on abundant documentation of climate change impacts on human–ecosystem interactions, there is *high confidence* that these impacts have negative consequences for subsistence, recreation, and spiritual practice. Some geographies and communities are more impacted than others, and fine-grained or predictive understanding of which communities and practices are most at risk is still being developed.

Key Message 6.2

Changes in Climate and Land Use Affect Land-System Resilience

Description of Evidence Base

The adverse impact of climate change (e.g., increased mean temperature, extreme heat, drought) on the resilience of land systems is supported by theory and observational studies involving a wide array of ecosystems, with overwhelming evidence in the United States coming from ecosystems that are increasingly influenced by drought, wildfire, and pests (e.g., Williams et al. 2019[21]). There is also strong evidence for how the loss of natural lands leads to degradation of ecosystem services that are slow to recover (e.g., Isbell et al. 2019[142]). However, the extent to which different ecosystems may recover or management choices are able to maintain or rebuild ecosystem resilience is not well known.

Globally, there is a large body of literature on how land-use and land-cover changes might influence local and regional climate, and findings are often region- and scale-dependent. This assessment focuses on studies over subregions of the United States, some based on observational data analysis and others based on numerical model experiments. Of the observation-based studies, some took a space-for-time approach by comparing climate trends over different land types (e.g., irrigated versus rainfed cropland, forest versus cropland; e.g., Mueller et al. 2016[146]), while others were based on observations before and after sudden land-cover changes (e.g., Li et al. 2022[106]). In numerical modeling studies, land-use or land-cover changes were imposed over a corresponding subregion (e.g., intensification or irrigation over cropland in the central US or Midwest, converting cropland to forest in the Southeast) with experiments designed to distinguish the impact of land-use change from the impact of greenhouse gas warming. These studies compared model results with observed climate trends to enable the attribution of observed climate phenomena to land-use practice or land-cover changes (e.g., Alter et al. 2018[145]). Findings from these studies are mostly consistent.

Warming-induced intensification of rainfall increases the nitrate leaching from cropping systems to surface water and groundwater, which exacerbates the environmental effects of increased fertilizer application. Different land-use practices (e.g., no-tillage management versus conventional tillage) may influence nitrate leaching, but the impact remains uncertain based on recent literature, which limits the extent of this chapter's assessment on this aspect.

A rich literature base supports the idea that while interactions between climate change, land use, land-cover change, and disturbance increase the risks of adverse impacts, they also provide multiple opportunities to reduce or lessen those impacts and ensure resilience.

Major Uncertainties and Research Gaps

The impact of urbanization on precipitation and other storms has been a topic of increasing research interest. Studies based on numerical modeling found a clear signal related to the enhancement of storm severity and precipitation (e.g., Debbage and Shepherd 2018[119]). However, observational data show a large degree of uncertainty and regional dependence. This is an important research gap.

Although geographically widespread increases in intense rain are evident, flooding trends are not consistently apparent at present.[118] Whether intense rain leads to flooding depends on soil type and land use, urban water-conveyance capacity, and how well the urban storm drainage system is maintained.

There are important uncertainties related to interactions between invasive species, disease, and natural disturbance. There is some evidence that changes in temperature and precipitation, as well as altered fire regimes, may negatively impact the competitive ability of native species, facilitating invasion by pests and pathogens (e.g., Ravi et al. 2022[41]). However, the outcomes are variable and seem to depend on multiple factors.

Research gaps and uncertainties also exist for the interactions of climate change with land-based renewable energy. Current research provides inconclusive results across the United States for all technologies.[136]

Description of Confidence and Likelihood

Based on a large literature base (e.g., Holden et al. 2018;[87] Stephens et al. 2018[93]), there is *high confidence* that climate change and climate change–related amplification of disturbance effects have a negative impact on ecosystem resilience.

Studies based on different methodologies (including observational data analyses and numerical model experiments) are consistent in suggesting that agricultural intensification and/or irrigation cause cooling and the increase of precipitation and atmospheric humidity in the central US during summer; similar climate effects were found in fall and winter resulting from the increase of forest cover in the southeastern US due to agricultural abandonment. Increased flooding was observed in urbanized basins (e.g., Hodgkins et al. 2019[120]); elsewhere, there is no clear signal of increased flooding risks despite the strong increase in extreme precipitation (frequency and intensity). Based on this understanding, there is *high confidence* that climate and land-use change interact and that these interactions present challenges as well as opportunities for maintaining ecosystem resilience.

Key Message 6.3

Mitigation and Adaptation Priorities Will Increasingly Constrain Future Land-Use Options

Description of Evidence Base

The evidence base describing Shared Socioeconomic Pathway (SSP) scenarios is large and well developed, having already been used in multiple international studies by the Intergovernmental Panel on Climate Change (e.g., IPCC 2022[180]) and the Coupled Model Intercomparison Project simulations. The "storylines" from the SSPs are developed by integrated assessment models (IAMs) into modeled projections of societal changes across multiple sectors. These scenarios provide alternative realizations of future societal pathways that are consistent with specified climate targets.[149,150] As such, they are useful for examining the range of possible challenges and changes facing our society over the rest of this century, although they do not provide predictions or probabilities of future trends.[198]

The Land-Use Harmonization 2 (LUH2) dataset provides a spatially explicit downscaling of the subset of SSP results used for the Scenario Model Intercomparison Project,[199] harmonizes them with historical land-use reconstructions, and provides a consistent data input for Earth system model simulations.[151] The LUH2 data provide global annual gridded (0.25° resolution) data of the fractional area occupied by 12 different land-use states, all transitions between those states, and land management data. The Land Change Monitoring, Assessment, and Projection (LCMAP) product described in the Introduction is a high-resolution annual land-cover dataset. That product complements the National Land Cover Database (NLCD),[200] which has greater thematic detail but is updated less frequently.

US agricultural land use in particular is tracked by a variety of surveys (e.g., the Census of Agriculture [CoA]) and longitudinal methods (e.g., the National Resources Inventory [NRI]), producing data that can be used to calibrate and validate the previously described remote sensing–based datasets.[8,137,201] Agricultural production is tracked through government statistics (e.g., the USDA National Agricultural Statistics Service), and crop yields are evaluated at finer spatial scales through crop insurance programs and combine yield monitors. The annual Inventory of US Greenhouse Gas Emissions and Sinks[55] estimates emissions from US land-use change, using agricultural area data from NRI and other sources.

Understanding of mitigation-driven land-use changes draws on the large IAM scenario evidence base described previously. Additionally, the Princeton Net-Zero America Project[172] is among the first to project where renewable electricity generation infrastructure might be sited at relatively fine spatial resolution.

Major Uncertainties and Research Gaps

Although human land-use activities have historically resulted in a net source of carbon emissions to the atmosphere, there is considerable uncertainty in these, and future, estimates.[202]

The SSP scenarios and harmonized land-use datasets are generated with a global focus. Although they can be analyzed and used for specific regional and national impacts, they are not likely to have US-specific levels of detail. In addition, the national-to-regional focus of these scenarios prevents the consideration of many societal equity and justice issues. Inequality and governance are included as drivers of land-use change in the SSPs, where they are used primarily to address inequality between countries and regions.[203] The SSP datasets used by LUH2 were each produced by a single IAM; it is possible that alternative IAMs would represent land-use differently within each SSP, and those potential differences were not explored here. There are also very few studies that provide short-term predictive forecasts of national-level land-use changes over the next 1–2 decades.[204] SSP scenario analyses do not include climate feedbacks to the future scenarios, but other studies using coupled human–climate models[205] show that climate change is expected to modify the future land-use choices society is able to, or desires to, make.

Future agricultural land requirements will depend on various difficult-to-assess factors such as changing dietary preferences and climate change effects on crop yields. While IAM studies typically assume that historically observed rates of crop yield increase will continue into the future, more detailed modeling efforts such as the Agricultural Model Intercomparison Project (AgMIP)[156] suggest that climate-driven reductions in corn yield in the western US may be clearly observable in as little as two decades under pessimistic emissions scenarios (SSP5-8.5), for example. The potential of in situ adaptation practices (e.g., adoption of different crop varieties or planting dates) to mitigate the severity of climate-driven disruptions is an active area of study, but the literature base on climate-driven shifts in crop cultivation range is still very limited.[159] Studies show that dietary shifts away from animal products toward plant products have a large biophysical potential for reducing total agricultural land use and supporting natural ecosystem restoration and land-based mitigation.[165,167,168] The SSP scenarios cover a range of dietary shift assumptions, including a shift toward low-meat diets in SSP1 and associated market and trade implications.[150]

The efficacy of existing land-based mitigation measures is often debated. For example, estimates of the mitigation value of US corn ethanol production diverge significantly[187,188] depending on assumed counterfactual land use in the absence of ethanol production and the degree to which diversion of finite arable land might lead to unintended agricultural expansion elsewhere. While remote sensing provides an invaluable tool for tracking deforestation, it can struggle to differentiate more subtle land-use changes with similar land cover (for example, unmanaged native grasslands, rangeland, pastureland, hay land, cropland–pasture, idled cropland, and conservation reserves), making it difficult to distinguish between permanent agricultural expansion versus transient agricultural intensification.[206] This ambiguity contributes to the debate around the viability and desirability of wide-scale land-based mitigation and carbon dioxide removal (CDR) measures in future decarbonization scenarios.

Description of Confidence and Likelihood

The land-use consequences of agricultural technology improvement (e.g., per-area crop yields, management intensity) and demand for land-based mitigation (including bioenergy and various CDR measures) are well explored in SSP scenario analyses.[150,205] Other collaborations (e.g., AgMIP) have explored the interaction between crop productivity and future climate change beyond what has been possible in integrated assessment modeling. Together, these literatures point to the influences of technology, mitigation needs, and climate change on land-use futures, hence the *high confidence* rating.

Primary data on cultivated cropland area and/or total cropland area are available via remote-sensing datasets (NLCD and LCMAP), longitudinal studies (NRI), and surveys (CoA). The longer-duration NRI and LCMAP datasets support a net decline in US cropland area over the last three and a half decades for which data are available, consistent with longer-term land-use records showing a mid-20th-century peak in US cropland area.[151] All four of these primary datasets are consistent with partial rebound of cropland area more recently, although with some disagreement around the starting year (as early as 2001 in NLCD or as late as 2012 in CoA) and magnitude of that rebound. Based on the agreement of these different primary data sources, there is *high confidence* of a long-term decline in US cropland area followed by a more recent rebound.

The LUH2 future scenarios all show stable or declining cropland use across the range of population growth and dietary shifts represented in the SSPs, although these scenario comparisons are not designed to represent the likelihood of different futures. Other literature suggests ongoing challenges in maintaining agricultural system resilience[155] in the face of a changing climate. Thus, continuation of the trend of declining land use is given a *medium confidence* rating, since there is not only evidence for multiple enabling preconditions but also key risks that are not captured in most scenario assessments.

The scenario assessment literature is consistent in identifying expanded electricity generation from renewable sources (i.e., wind and solar) and more widespread electrification of energy end use as preconditions for decarbonization of the energy sector.[171] This is consistent with recent trends of accelerating wind and energy deployment driven by the comparatively low cost of these energy sources, as well as policy support (e.g., through the Inflation Reduction Act), hence the *very likely*, *high confidence* rating. However, decarbonization scenarios have been widely criticized for over-reliance on land-intensive, technologically immature, or potentially unsustainable land-based mitigation and CDR measures,[207,208,209] and a variety of alternative scenarios that avoid land-intensive CDR have been developed.[190] Considering this, the statement about widespread land-use change for land-based mitigation is assigned a *low confidence* rating.

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Fifth National Climate Assessment: Chapter 7

Forests



Chapter 7. Forests

Authors and Contributors

Federal Coordinating Lead Author

Christopher J. Fettig, USDA Forest Service, Pacific Southwest Research Station

Chapter Lead Author

Grant M. Domke, USDA Forest Service, Northern Research Station

Agency Chapter Lead Author

Anne S. Marsh, USDA Forest Service, Washington Office

Chapter Authors

Michelle Baumflek, USDA Forest Service, Southern Research Station
William A. Gould, USDA Forest Service, International Institute of Tropical Forestry
Jessica E. Halofsky, USDA Forest Service, Pacific Northwest Research Station
Linda A. Joyce, USDA Forest Service, Rocky Mountain Research Station
Stephen D. LeDuc, US Environmental Protection Agency, Office of Research and Development
David H. Levinson, USDA Forest Service, National Stream and Aquatic Ecology Center
Jeremy S. Littell, US Geological Survey, Alaska Climate Adaptation Science Center
Chelcy F. Miniat, USDA Forest Service, Rocky Mountain Research Station
Miranda H. Mockrin, USDA Forest Service, Northern Research Station
David L. Peterson, USDA Forest Service, Pacific Northwest Research Station
Jeffrey Prestemon, USDA Forest Service, Southern Research Station
Benjamin M. Sleeter, US Geological Survey, Western Geographic Science Center
Chris Swanston, USDA Forest Service, Washington Office

Technical Contributors

Ning Liu, USDA Forest Service, Southern Research Station
D. Max Smith, USDA Forest Service, Rocky Mountain Research Station
Brian F. Walters, USDA Forest Service, Northern Research Station

Review Editor

Brooke Eastman, West Virginia University, Department of Biology

Cover Art

Jenny Helbraun Abramson

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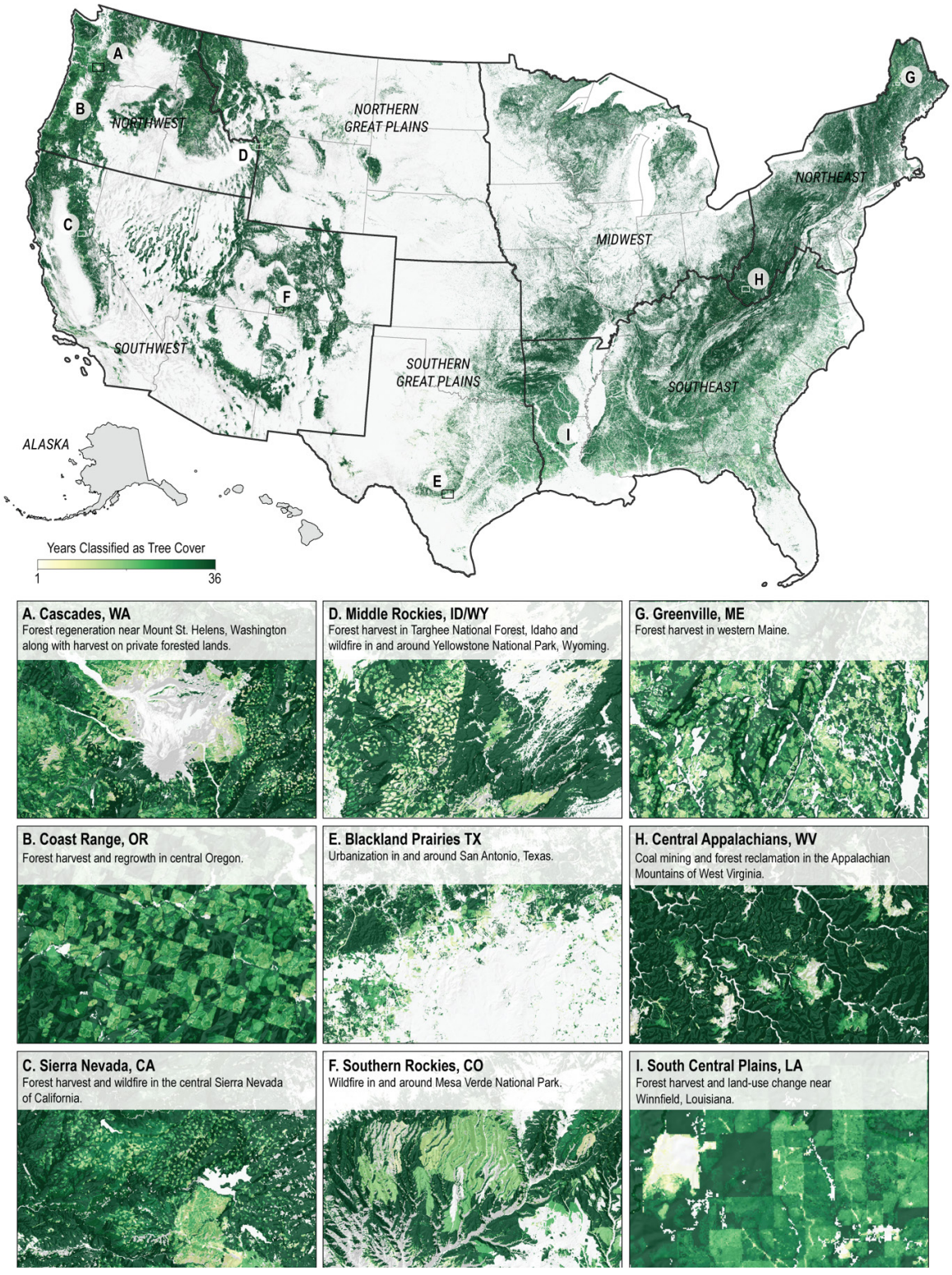
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Introduction

Forest ecosystems provide ecological, economic, and social goods and services (hereafter ecosystem services) to natural systems and humankind. These include air purification; regulating water quantity and quality; provisioning fish and wildlife habitat, food, medicine, shelter, wood, and other forest products; provisioning aesthetics, outdoor recreation, and spiritual renewal; and regulating climate through carbon transfers and other processes.[1] The livelihoods, health, nutrition, and cultural practices and traditions of many Indigenous and Tribal Peoples depend on forest ecosystems (Ch. 16). Social and economic drivers influence how and when forests are managed to maintain or restore ecosystem services critical to human health and welfare.

Forests represent more than one-third (766 million acres) of the land base in the US, with an additional 125 million acres of trees outside of forests in woodlands and developed areas. The amount of forest and tree cover has remained relatively stable over the last 100 years despite substantial land-use change into and out of forest and tree cover, especially in recent decades (Figures 7.1, 6.2).[2] Forest land area and tree cover have declined slightly in the contiguous US in the last two decades due mostly to cropland expansion and urbanization (Figure 6.4),[3,4] including expansion of the wildland–urban interface (WUI).[5] Forests contributed more than 4% of total US manufacturing gross domestic product in 2020 (nearly $336 billion in 2022 dollars), and the forest products industry is among the top 10 manufacturing sector employers in the US.[6]

Tree Cover Dynamics

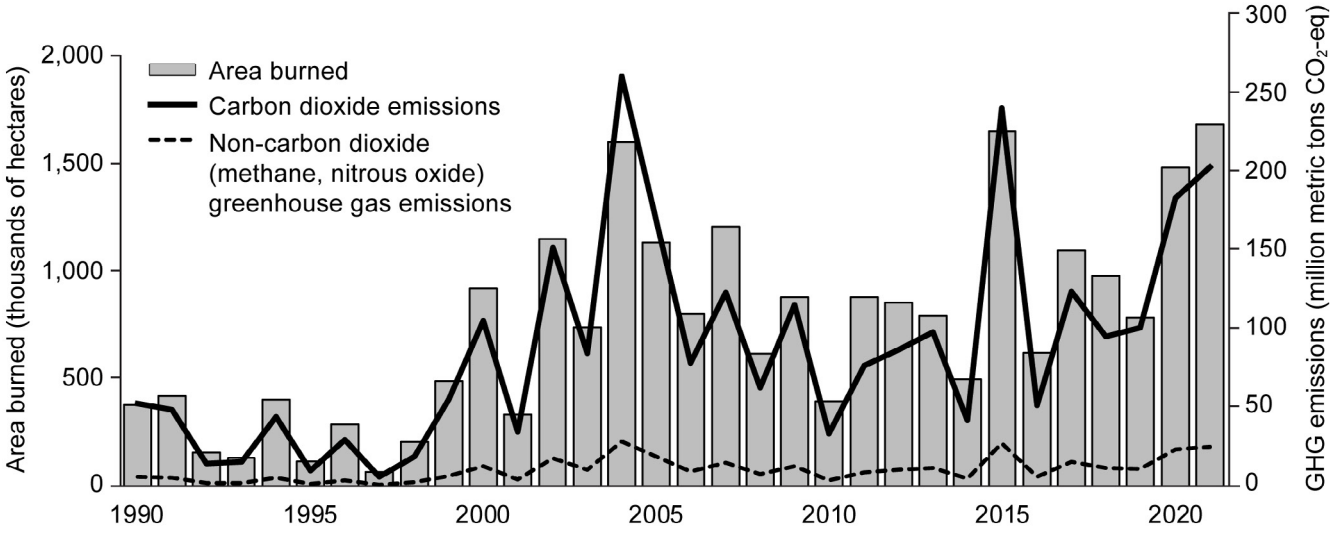


The persistence of tree cover in the United States varies due to many driving forces.

Figure 7.1. This figure shows the number of years each 30 m by 30 m pixel was classified as forest cover during 1985–2020. Insets (**A–I**) show that patterns of forest cover vary considerably across regions, often due to differences in the factors causing forest change. Patterns in tree cover change in the US are driven, in large part, by climate-related disturbances, land use, and land-use change. Data were unavailable for Alaska, Hawai'i and the Affiliated US Pacific Islands, and the US Caribbean. Figure credit: USGS.

The vulnerability of US forests to climate change and climate-related disturbances varies (relative to natural variability) due to differences in biophysical conditions and local and regional variations in climate (Chs. 2, 3). For example, although 21st-century temperatures (2001–2020) have increased almost everywhere in the US (relative to 1951–1970), this warming has not occurred uniformly across the US (KM 3.4; Figure 3.11). Due to these differences, the capacity of some US forests to provide ecosystem services is increasingly affected by climate change and climate-related disturbances (KMs 7.1, 7.2).[7] For example, the amount of forest burned and greenhouse gas (GHG) emissions from fires have increased substantially since 1990, mostly in the West, with three of the five worst wildfire years (based on area burned and GHG emissions) occurring since 2015 (Figure 7.2).[3] Proactive adaptation will assist the provisioning of ecosystem services from forests. Examples of adaptation in US forests have proliferated since 2017 (KM 7.3; Ch. 31) on federal, state, local, Tribal, and private lands (e.g., Moser et al. 2019;[8] USDA 2022,[9] 2021[10]). The effects of climate change on forests in specific regions of the US are discussed in several of the regional chapters (e.g., Chs. 21–24, 27–29).

Estimated Annual Greenhouse Gas (GHG) Emissions from Wildfires and Prescribed Fires



The amount of forest area burned and associated greenhouse gas emissions have increased in recent decades in the United States.

Figure 7.2. Estimated forest area burned and greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) from wildfires and prescribed fires in the contiguous US and Alaska have increased since the late 1990s. Climate change is affecting the likelihood and scale of wildfires in US forests. In some cases, wildfires (particularly in the western US) have slowed or stopped recovery of forests from previous disturbances, reducing their capacity to sequester and store carbon. Adapted from Domke et al. 2023.[3]

Key Message 7.1

Forests Are Increasingly Affected by Climate Change and Disturbances

Climate change is increasing the frequency, scale, and severity of some disturbances that drive forest change and affect ecosystem services (*high confidence*). Continued warming and regional changes in precipitation are expected to amplify interactions among disturbance agents (*likely*, *high confidence*) and further alter forest ecosystem structure and function (*likely*, *high confidence*).

Climate change affects disturbances such as wildfires, insects, diseases, and land uses, as well as the interactions among these disturbances, all of which shape forest ecosystems through changes in growth, mortality, regeneration, and recruitment of vegetation over space and time (Figure 6.1 in Vose et al. 2018[11]). Disturbances altered by climate change pose risks to current and future forest health (i.e., the extent to which ecosystem processes are functioning within their natural range of historical variation) and will affect forest conditions across landscapes for years to centuries. Weather events such as droughts, hurricanes, windstorms, and floods may exacerbate disturbance effects, especially in extreme cases (Figure 7.3; Chs. 8, 9). The exposure and sensitivity of forests to climate change and climate-related disturbances vary with disturbance, forest condition, management history, and the rate and magnitude of change.

Coastal Ghost Forest



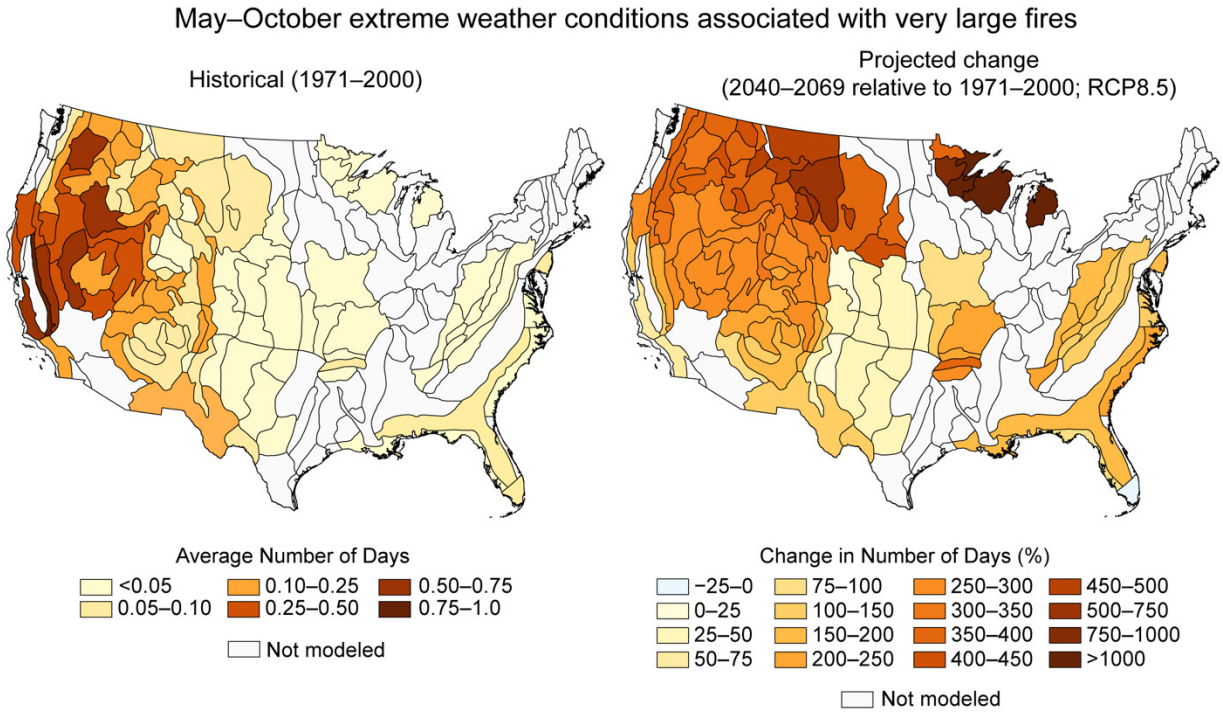
Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion.

Figure 7.3. The photo shows a coastal ghost forest (foreground) near Blackwater National Wildlife Refuge, Maryland. As sea levels rise in response to climate change, the replacement of coastal forests with tidal wetlands will affect many ecosystem services, including storm surge buffering capacity. Photo credit: ©Matthew L. Kirwan, Virginia Institute of Marine Science.

Climate change is affecting the likelihood and scale of wildfires in US forests. For example, the amount of forest burned by wildfires in the West has increased relative to the mid- to late 20th century[12,13] due, in part, to warming increasing vapor pressure deficits and rates of evapotranspiration (KM 4.1),[12,14] as well as decreases in precipitation (KM 4.1).[15] Fire activity is projected to increase with further warming and reductions in precipitation,[14,16] although increases depend on regional fuel types and may eventually decrease in some forests due to reductions in fuel loads.[17] The area burned by high-severity wildfires (e.g., stand-replacing fires) has increased in the West since 1985 by about eightfold,[18] partly due to warmer, drier conditions (Figure 7.4; KM 2.1). Where abundant fuels are available, western US forests have experienced an increase in the proportion of area burned at high severity, especially in the Southwest (KM 28.5).[18] Increased fire severity is expected to become more widespread in US forests in the future.[19] Atypical re-burns and levels of fuel flammability that were historically rare are expected to become more common (Focus on Western Wildfires).

Determining the effects of climate change on wildfires is more difficult in regions outside the West, for example, in areas where prescribed fire use has changed substantially over time (Southeast), where wildfire was historically rare (Northeast), and where forests represent a small portion of the landscape (agricultural regions in the central US). Furthermore, fire intensity (energy released during wildfire) and severity depend on fuel availability and flammability, which are directly affected by management (including wildfire suppression) and land use,[20] as well as climate-driven changes in weather. However, altered meteorological conditions (e.g., relative humidity and wind speed), especially extreme conditions promoting wildfire spread, have become more prevalent in recent decades[21] and are attributed, in part, to climate change (KM 2.2).[22] Changes in human demography in the WUI and increases in the ratio of human to natural fire ignitions[23] have combined with climate change to alter historical expectations of fire initiation and spread. One study found that a long-term trend in nighttime vapor pressure deficit, not simulated in climate models, explained recent fire managers' observations that the rates of spread of fires in the West slowed less at night.[24]

Very Large Fires



Conditions conducive to very large fires are projected to increase.

Figure 7.4. The left panel shows historical (1971–2000) values for the annual number of days in May through October with extreme weather conditions conducive to very large fires (VLFs; more than 12,000 acres). The right panel shows the percent change in the number of days for a projected future (2040–2069) climate under a very high scenario (RCP8.5). Changes are summarized by Bailey ecosections, which are areas of similar vegetation and climate defined by Bailey (2016).[25] The number of days with conditions associated with VLFs more than doubles in many ecosections, with more than a fourfold increase for parts of the Northwest, fivefold for the northern Rockies, and over sevenfold for the Upper Midwest. Projected conditions are an average of a 17-GCM (global climate model) ensemble selected for data availability. Areas with no color indicate lack of data (sufficient data are unavailable or where wildfires were historically rare). Data were unavailable for Alaska, Hawai'i and the Affiliated US Pacific Islands, and the US Caribbean. Figure credit: USGS.

In addition to wildfire, native and invasive (non-native) insects, diseases, and plants are important forest disturbances with climatic and non-climatic factors influencing their extent and effects. Tree mortality from bark beetles in the West has increased in the late 20th and early 21st centuries due, in part, to climate change (Box 7.1).[26,27,28,29] The effects of climate change on other forest insects and diseases are less certain. For example, white pine blister rust (a disease caused by the non-native fungus *Cronartium ribicola*) is expected to decrease where conditions become warmer and drier (Southwest) but increase where conditions become warmer and wetter (high-elevation subalpine forests).[30] Warming, altered precipitation patterns, extreme events, and disturbances all influence invasion pathways and may facilitate the establishment and spread of invasive species (KM 8.2).[31] In Hawai'i, climate change and the spread of invasive grasses have increased the frequency and extent of wildfires.[32] In the Southeast, warming temperatures have allowed cold-sensitive invasive species like kudzu to move farther north,[33] affecting forest structure and composition. Kudzu and other woody vines are stimulated by increased carbon dioxide (CO_2)[34] and in some cases outcompete trees and other plants.[35] Even in the absence of other disturbances, warming and drought are important drivers of tree mortality in the US and globally.[36]

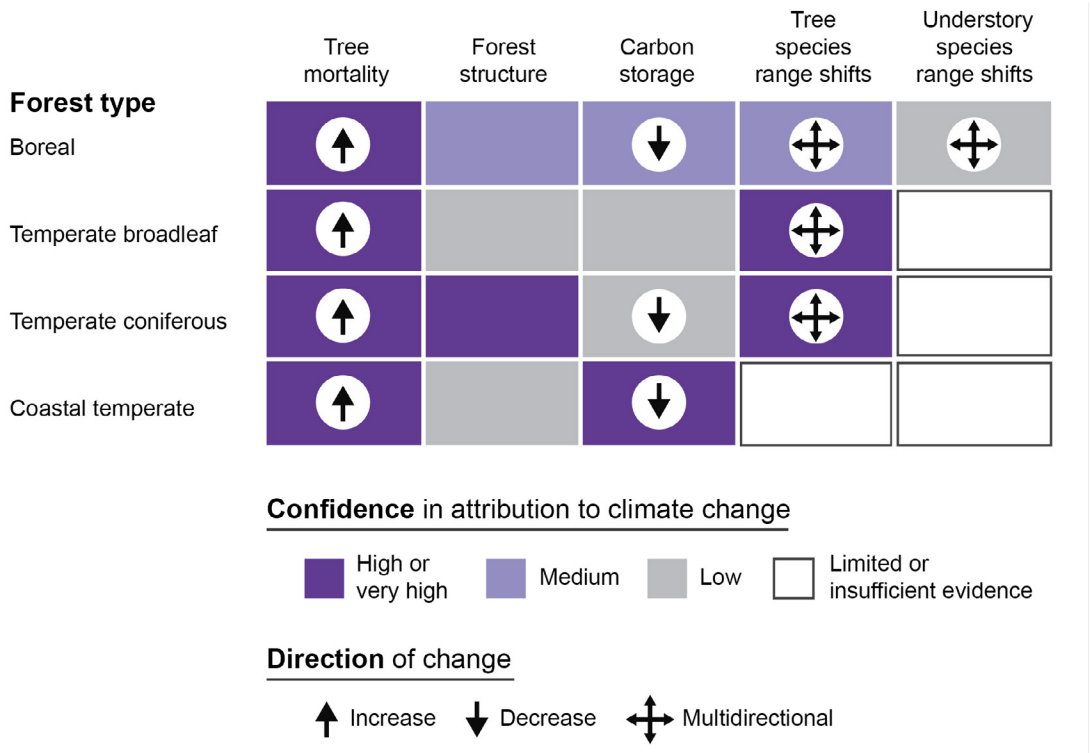
Sea level rise, another climate-related disturbance, affects the distribution, structure, and composition of forests (KM 9.2). Saltwater intrusion has reduced the health, diversity, and productivity of some coastal

forests in the East (Figure 7.3).[37] Sea level is projected to result in the loss of existing mangrove forests in many places in future decades.[38,39,40] However, warming during winter has facilitated northward migration of mangroves in the Southeast (Figure 7.7).[41]

Forest structure, function, and diversity are affected across a broad range of spatial scales (Figure 7.5). Variation in environmental conditions, historical and contemporary disturbances, management history, and land use have modified many forests, making them more vulnerable to droughts, wildfires, and other disturbances.[42] These disturbances accelerate tree mortality; alter tree and other plant species distributions, age and size distributions, and regeneration success; and can lead to conversion to non-forest ecosystems (e.g., Falk et al. 2022;[43] Stanke et al. 2021[44]).

Ecological transformations and shifts in forest habitats are occurring because of climate change (KM 8.1).[45] In some low-elevation forests in the West, tree regeneration over the last 20 years has been limited by unfavorable climate. High wildfire severity and low seed availability has further reduced postfire regeneration in some locations.[46,47] Eastern tree species migration is associated with increased seed production but is limited to some extent by the occurrence and distribution of large urban areas in the East.

Effects of Climate Change on Forests



Climate change and climate-related disturbances are affecting forests in the United States.

Figure 7.5. The figure shows recently documented effects, specific to individual forest types, that have been attributed to climate change and climate-related disturbances. Effects include increased tree mortality across all types with high confidence, changes in forest structure with variable confidence, less carbon storage across three of the four forest types, and variable shifts in plant species composition. Confidence levels reflect the uncertainty in attributions based on available literature. Arrows indicate the direction of change where suitable data exist. In the case of temperate forests, structure is changing but not in a unidirectional way. Boreal forest reflects changes only in Alaska. Assessments in the figure are based on recent relevant literature, and citations can be found in the metadata. Adapted with permission from Figure SPM.2 in IPCC 2022.[48]

Although the effects of climate change on tree species have been well studied, effects on understory plants are poorly understood.[49] In Wisconsin, shifts in understory plant species lag regional climate changes, but less so for species with broader site occupancies and larger seed masses.[50] In Oregon's Siskiyou Mountains, average temperature increases of about 3.6°F since 1948 have caused differing effects on plant communities. Low-elevation herb communities are now consistent with a hotter, drier climate and resemble plant communities in more southerly topographic positions. At higher elevations, herbs of northern biogeographic affinity have increased.[51]

Some management activities and land-use changes, especially rapid expansion of the WUI,[5] have reduced the adaptive capacity of forests to variations in climate and climate-related disturbances.[52,53,54] The WUI is more prevalent in the East but is expanding at a faster rate in the West.[5] In the East, forests in the WUI retain larger trees and aboveground biomass than less developed forests, but with less structural diversity (i.e., WUI forests have fewer saplings, seedlings, and dead trees). This raises concerns about diminished ecological function, reduced diversity of wildlife habitat, and vulnerability to warming.[55] In the West, wildfire exclusion in dry forests historically adapted to frequent wildfire has altered forest structure and composition, resulting in higher surface and canopy fuel loads and increased vulnerability to high-severity wildfire.[56,57]

Box 7.1. Bark Beetles and Climate Change

Bark beetles spend most of their lives within a host tree, feeding and reproducing beneath the bark. Climate change has increased the impacts of some bark beetles due to 1) warming, which in some cases has increased life cycles and decreased overwintering mortality of beetles within the host tree; and 2) drought, as drought-stressed hosts have compromised defenses and offer little resistance to colonization by bark beetles.[26,27,58] Warming during summer increases the probability of a spruce beetle completing its life cycle in one year compared to two years,[59] which has increased spruce beetle populations in some areas (Figure 7.6). In California, warming and drought incited mortality of more than 100 million trees during 2014–2017, most attributed to western pine beetles (Figure 7.6) colonizing ponderosa pines.[60,61] About 30% of the tree mortality in California was attributed to warming accelerating the life cycle of western pine beetle, with the remainder attributed to increases in host susceptibility due to drought stress.[29] The biomass of ponderosa pines in California may not return to levels that occurred prior to the drought due to future warming, droughts, and western pine beetle outbreaks.[62]

Warming has allowed mountain pine beetles to erupt at elevations and latitudes where winters historically were cold enough to kill most mountain pine beetle brood within the host tree.[26] In New York and New England, a recent climate-driven range expansion of southern pine beetle resulted in a new bark beetle-host interaction in pitch pine forests.[63] In Alaska, an ongoing spruce beetle outbreak has affected more than 1.6 million acres since 2016 and expanded into the Alaska Range,[27] threatening spruce forests in interior Alaska, where spruce beetle populations were historically regulated by cold winter temperatures.[64]

Bark beetle outbreaks are often detrimental to the provision of ecosystem services,[65] and can affect other disturbances and their effects on ecosystem services. For example, in some forests, mountain pine beetle outbreaks have increased the severity of wildfires[66] and the abundance of invasive weeds.[67] Silvicultural interventions such as thinning to reduce tree densities can be used to increase the resistance and resilience of some forests to bark beetles (KM 7.3), a relationship attributed to decreases in tree competition and associated increases in tree vigor, among other factors.[27]

Spruce and Pine Beetle Outbreaks



Outbreaks of spruce and pine beetles, partly attributable to climate change, are killing trees in the West.

Figure 7.6. These photos show a spruce beetle outbreak on the Bridger–Teton National Forest in Wyoming (**left**) and a western pine beetle outbreak on the Sierra National Forest in California (**right**). Discolored trees were colonized and killed by bark beetles. Warming and drought have increased the impacts of some bark beetles in US forests, affecting many ecosystem services. Photo credits: Christopher J. Fettig, USDA Forest Service.

Key Message 7.2

Climate Change Affects Ecosystem Services Provided by Forests

Climate change threatens the ecosystem services forests provide that enrich human lives and sustain life more broadly. Increasing temperatures, changing precipitation patterns, and altered disturbances are affecting the capacity of forest ecosystems to sequester and store carbon (*high confidence*), provide clean water and clean air (*high confidence*), produce timber and non-timber products (*high confidence*), and provide recreation (*medium confidence*), among other benefits. Future climate effects will interact with societal changes to determine the capacity of forests to provide ecosystem services (*likely, high confidence*).

Some effects of climate change and climate-related disturbances on ecosystem services and their associated economic benefits are gradual, driven by annual or seasonal warming, altered precipitation patterns, or sea level rise. Others are more rapid, driven by extreme events such as droughts, hurricanes, or heatwaves. Co-occurrence and/or interactions among disturbances (compound disturbances) can amplify the effects of individual disturbances on ecosystem services (Box 7.1; Figure 7.7; KM 2.3).[68,69]

Climate change is projected to affect forest growth domestically and internationally, wood and paper markets (e.g., Tian et al. 2016[70]), and the amount of carbon stored in harvested wood products (Box 7.2; KM 12.2; e.g., Johnston and Radeloff 2019[71]). However, the strength of these effects is uncertain due to disturbances, such as droughts, wildfires, insects, and diseases, that limit forest growth.[72] Forest management actions taken in response to climate change can also affect timber product outputs, carbon, and associated ecosystem services (e.g., Creutzburg et al. 2017[73]). Sea level rise also directly and indirectly affects timber output and carbon storage through loss of coastal forests to saltwater intrusion and housing losses and rebuilding, with a projected 800,000 new residential units needed in the US by 2050 to accommodate relocations due to sea level rise under a very high scenario (RCP8.5).[74]

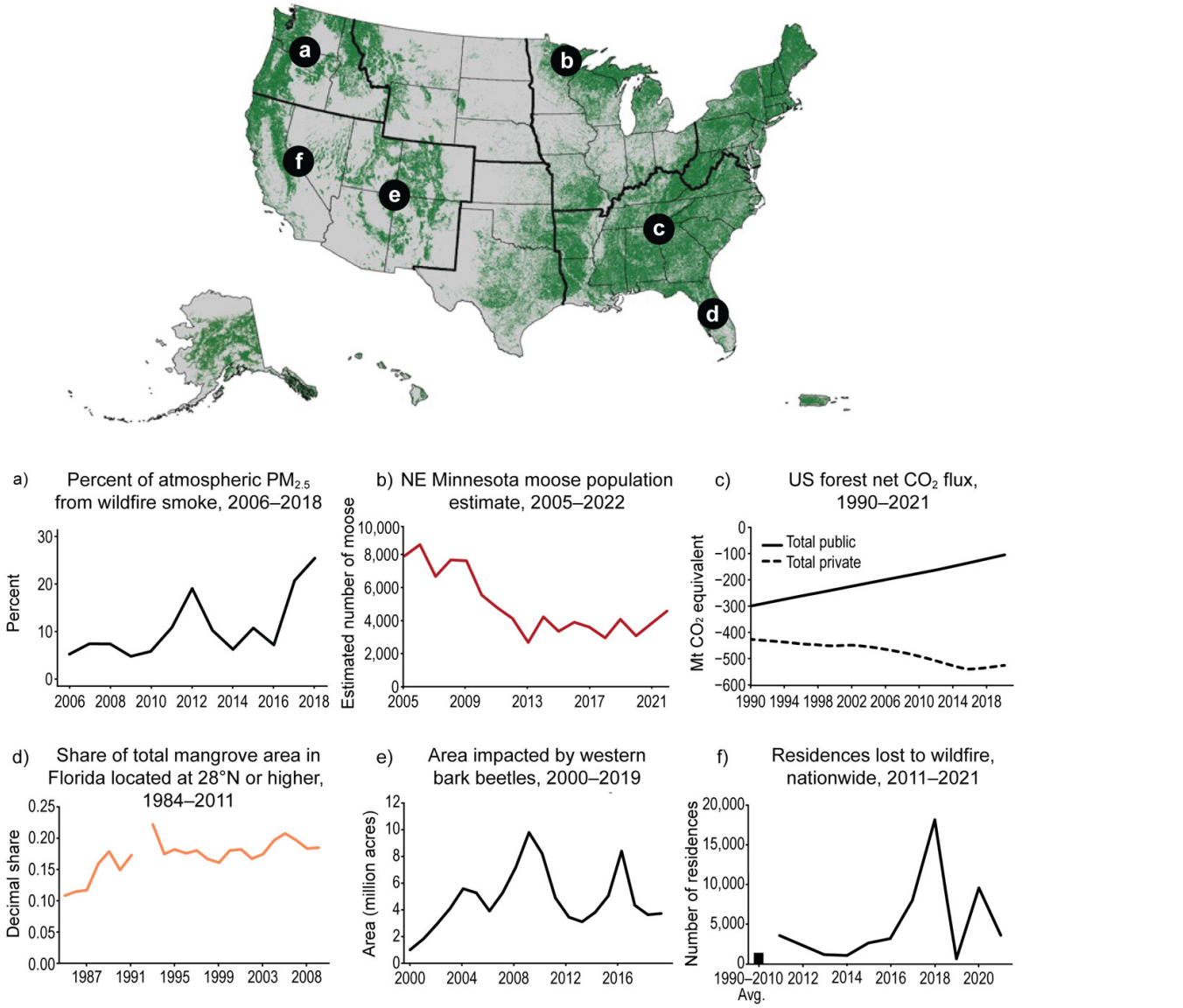
Climate change is altering the ranges and abundances of some plants and fungi used for food, medicine, and other purposes. Reduced snow depth, for example, can increase plant injury and mortality through increased exposure of tissues to frosts,[75,76,77] as well as reduced microbial biomass and activity.[78,79] Many plants and fungi have precise ecological requirements and narrow geographic ranges, leaving them vulnerable to climate change.[80] Some species are at their range limits, unable to adapt to rapidly changing conditions.[81] Effects differ by plant and fungal species, relating to their sensitivity and adaptive capacity.

Climate change affects heritage values, cultural identity, and spiritual connections associated with forests, exacerbating environmental injustices affecting Indigenous and Tribal food sovereignty, health, cultural practices, and knowledge transmission (Chs. 16, 20).[82] Examples of culturally significant species affected by climate change include salmon, brook trout, oaks, pinyon pine, and whitebark pine (Box 7.3).[83,84,85,86,87] In 2023, whitebark pine was listed as a threatened species by the US Fish and Wildlife Service, with white pine blister rust, mountain pine beetle, altered wildfire patterns, and climate change identified as major threats to its existence.[88] Climate-related changes highlight fluctuating consistency, timing, and availability of culturally significant foods, fibers, and medicines.[89,90,91]

Climate change decreases some forest-based recreational activities and increases others. For example, warming and reduced snowpack have had negative effects on winter sports (e.g., cross-country skiing, snowshoeing, and snowmobiling) and positive effects on warm-weather activities, with mixed effects on water-based activities.[92] Participation in fishing and motorized water activities is projected to increase in the North, while motorized water activities are projected to decrease in parts of the West.[93]

Increases in the amount of forest burned by wildfires are creating negative human health effects and growing economic losses.[94] Increases in wildfire smoke are increasing respiratory and cardiovascular-associated hospitalizations (KM 14.2; Focus on Western Wildfires)[95] and out-of-hospital cases of cardiac arrest.[96] Chemicals mobilized into the environment from wildfire-ignited structures and infrastructure can differ from those emitted from burning forest fuels, potentially increasing human health concerns (KM 14.2).[97,98]

Forest Ecosystem Services



Climate change has affected the provisioning of forest ecosystem goods and services in the United States.

Figure 7.7. (**a**) Increases in fine particulate matter air pollutants ($PM_{2.5}$) caused by wildfires degrade air quality and increase human health risks (data for Alaska, Hawai'i, Puerto Rico, US Virgin Islands, and US-Affiliated Pacific Islands are not available). (**b**) Reduction in moose hunting opportunities stems from climate-related increases in parasites; declines in hunting opportunities have also been noted in the western US.[99] (**c**) Increased tree mortality is shrinking carbon sequestration in public forests (Mt is millions of metric tons). (**d**) Northward migration of mangroves is displacing saltwater marshes, altering coastal storm protection and affecting recreation (data for 1992 are not available). (**e**) Increased tree mortality by western bark beetles lowers home values through reduced environmental amenities.[100] (**f**) Housing losses due to wildfires increased by fivefold in the 2010s compared to the average from 1990 to 2010, with substantial interannual variability; data exclude losses from US-Affiliated Pacific

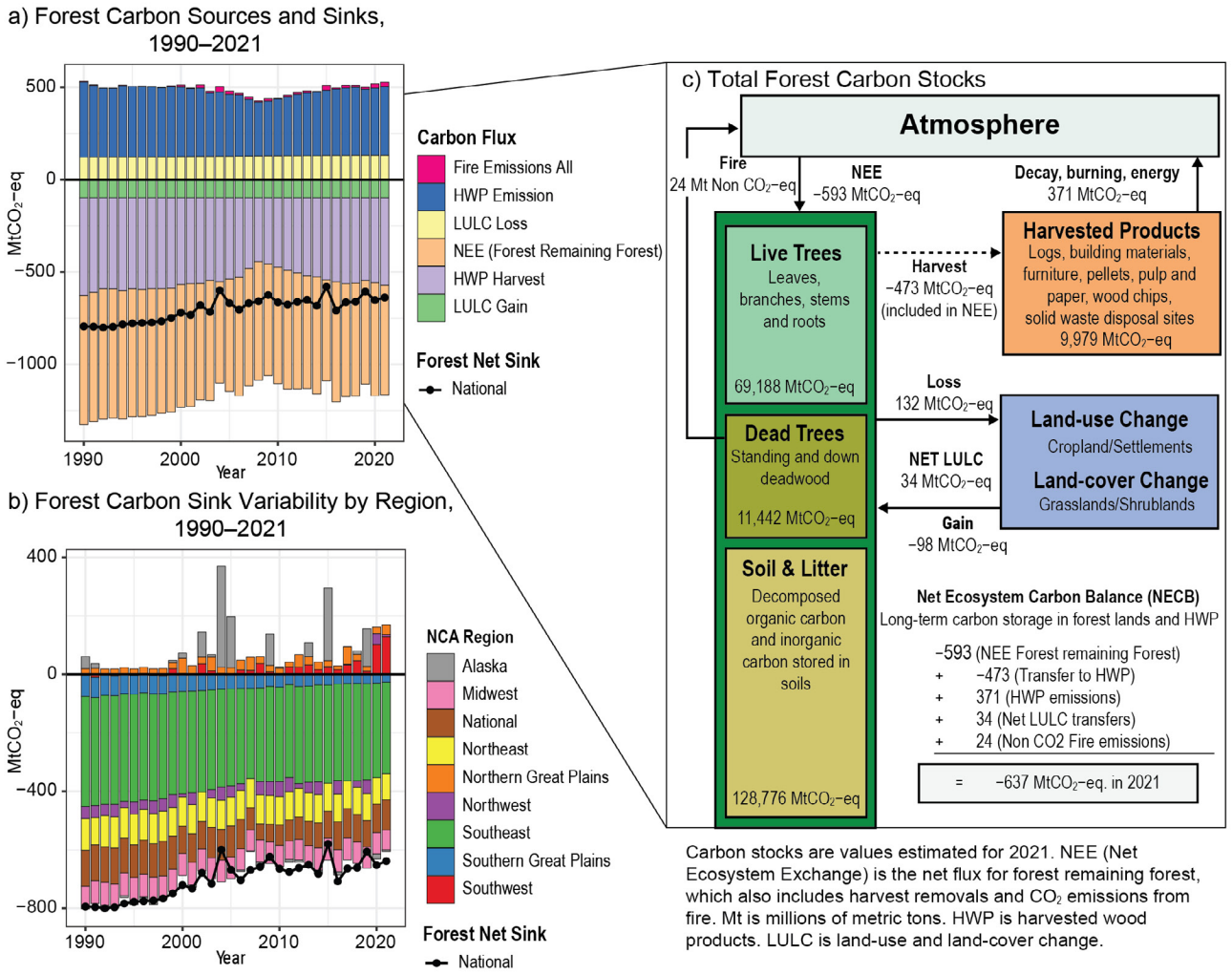
Islands. Notes: Map excludes depictions of forest area for the US Virgin Islands and US-Affiliated Pacific Islands due to the large scale of the map. US Virgin Islands forest area is 46,967 acres.[101] Forest areas for US-Affiliated Pacific Islands are as follows: Federated States of Micronesia (143,466 acres), Marshall Islands (23,252 acres), Northern Mariana Islands (75,407 acres), Palau (90,685 acres), American Sāmoa (43,631 acres), and Guam (63,833 acres); US Affiliated Pacific Island summary data are from sources cited in Lugo et al. 2022.[102] Figure credits: (top) USDA Forest Service; (a) adapted with permission from Burke et al. 2021;[103] (b) USDA Forest Service; (c) adapted from Domke et al. 2023;[3] (d) USDA Forest Service; (e) adapted from Fettig et al. 2022;[27] (f) USDA Forest Service.

Extreme events have been linked to declines in populations of amphibians, birds, fish, invertebrates, mammals, plants, and reptiles (KM 8.2).[104] Recent insect population declines have been attributed, in part, to climate change, with wide-reaching consequences.[105,106] Climate change is increasing the intensity of hurricanes in the East and their associated rainfall,[107,108] although projected changes in the frequency of hurricanes due to warming are uncertain (Chs. 2, 3; e.g., Sobel et al. 2021[109]). Increased intensities of hurricanes could affect the structure and function of forests and wildlife habitat (e.g., Brown et al. 2011[110]). Mobile species or species capable of rapid population growth (e.g., invasives) generally benefit from extreme events and abrupt disturbances.[104]

Box 7.2. Forests and Carbon

Carbon is continuously cycled between the Earth and atmosphere. Forests help regulate climate, as live plants remove carbon dioxide (CO_2) from the atmosphere through photosynthesis, facilitating maintenance and growth, and release some of that carbon through respiration. Forest ecosystems are the largest terrestrial carbon sink on Earth.[111] In the US, the amount of carbon stored in forests (primarily in soils and trees), as well as in harvested wood products that are either in use (e.g., paper, plywood) or in solid waste disposal sites (e.g., landfills), is equivalent to nearly three decades of fossil fuel emissions. On average, between 2017 and 2021, forest ecosystem carbon uptake has offset the equivalent of more than 13% of economy-wide CO_2 emissions each year.[3] In recent decades, the rate of forest carbon sequestration has slowly declined, in part due to increasing frequency and severity of climate-related disturbances, leading to interannual variability in the forest carbon sink and abrupt (e.g., wildfire) and/or gradual (e.g., insect outbreak) transfers of carbon to the atmosphere, dead organic matter pools (dead wood, litter), and soils (Figure 7.8; KM 6.1).[112,113] In some cases, climate-related disturbances have slowed or stopped recovery of forests, reducing their capacity to store carbon (Figure 7.8b),[62,114,115,116] and these trends are projected to continue under multiple climate, land-use, and socioeconomic scenarios. Human activities such as forest management (e.g., timber harvesting, prescribed fire, and other silvicultural interventions) are also major drivers of forest ecosystem carbon dynamics. Harvesting, for example, results in the transfer of some carbon stored in live and dead trees to the atmosphere as well as to harvested wood products and may alter the capacity of forest ecosystems to store new carbon.[112,117] Land-use changes, including cropland expansion and urbanization, have also contributed to the decline in carbon sequestration and/or storage.[115,118] Yet managing forest ecosystems, including forest soils,[119] for the purposes of carbon sequestration and/or storage, along with many other ecosystem services, remains a relatively cost-effective strategy for mitigating climate change (KM 6.3; Ch. 32).[112,120,121,122]

Forest Carbon Sink



Carbon stocks are values estimated for 2021. NEE (Net Ecosystem Exchange) is the net flux for forest remaining forest, which also includes harvest removals and CO_2 emissions from fire. Mt is millions of metric tons. HWP is harvested wood products. LULC is land-use and land-cover change.

The forest carbon sink has declined in recent decades in the United States, with substantial interannual variability.

Figure 7.8. The figure shows (**a**) the interannual variability in forest carbon sources and sinks during the period 1990–2021; (**b**) the interannual variability in the forest carbon sink in the US by National Climate Assessment region during 1990–2021; and (**c**) the total forest carbon stocks by ecosystem pool (boxes) and mean annual transfers among the atmosphere and forest ecosystem pools, harvested wood products, and land conversions (arrows) in 2021. Negative estimates indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfer between ecosystem pools or land categories). Forest ecosystems are the largest carbon sink in the US. There is substantial interannual variability in greenhouse gas emissions and removals from forest land that is driven, in large part, by climate-related disturbances, land use, and land-use change. Figure credit: USDA Forest Service and USGS.

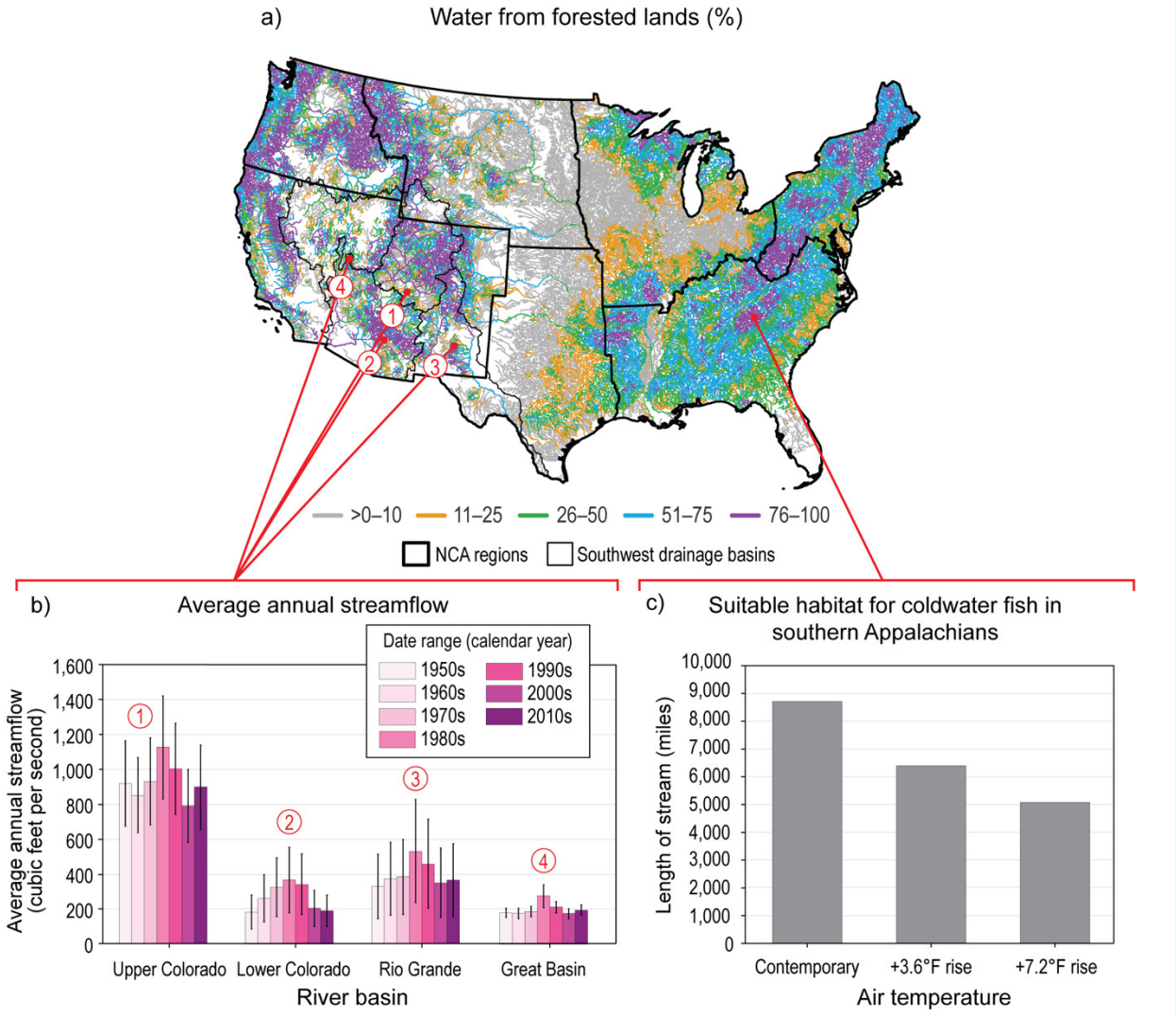
Box 7.3. Climate Change Effects on Forest Water Resources

Forests are a critical source of water in the US (Figure 7.9a),[123,124] and climate change and climate-related disturbances are directly and indirectly affecting the availability and quality of water from forests. Warming across the West has resulted in reduced snowpack and earlier snowmelt and spring runoff, decreasing downstream water availability (KM 4.1).[125] In the Southwest, higher temperatures and reduced precipitation have decreased streamflow in recent decades (Figure 7.9b).[126] Shifts in precipitation and declining snowpacks are decreasing the magnitude and/or frequency of flooding in some areas but increasing them in others (Figure A4.8).[127,128] Models indicate that climate change will affect flood events as some watersheds transition from snow-dominated precipitation, or mixed rain and snow, to rain-dominated precipitation.[129,130] Wildfires and other disturbances (e.g., bark beetle outbreaks) can also result in changes in the availability and quality of water from forests.[131,132] Following wildfires, tree mortality decreases evapotranspiration, thereby increasing water runoff and supply.[133] However, wildfire also increases the runoff of sediments, metals, and other chemicals into water bodies for several years or more after a fire,[134] with higher rates of drinking-water standard violations occurring in burned versus unburned watersheds.[135]

Climate change impacts on water quantity and quality in turn affect aquatic life. Warming, drought, and declines in snowpack increase stream temperatures,[136] decreasing coldwater fish habitat (Figure 7.9c).[137,138,139] Shifts in precipitation from snow to rain are projected in much of southern Alaska.[140] Anticipated effects include changes in streamflow timing and magnitude, with negative effects on salmon production and salmon habitat.[141]

Adaptation measures can reduce some of the effects of climate change on water resources. Management practices, such as reintroducing American beaver, have increased water storage in some landscapes[142] but have had mixed effects on water quality for salmon in the Northwest.[143] Maximizing riparian forest buffers reduces erosion and sedimentation, provides habitat for wildlife, and is projected to delay or reduce stream warming through enhanced shading.[144] Thinning and surface-fuel reduction can lessen the risk of high-severity wildfires in fire-prone buffers and adjacent forests in the West,[145,146] with the potential to reduce fire severity and consequently the effects of wildfire on water resources.[132]

Climate Effects on Forest Water Resources



Climate change and climate-related disturbances are affecting the availability and quality of water from forests in the United States.

Figure 7.9. Panel (**a**) shows the percent of surface water originating on forest lands across the contiguous US, illustrating that forests are a critical source of water. Panel (**b**) shows decadal average variations in average annual streamflow (measured in cubic feet per second [ft^3/s]) from Hydrologic Unit Code 8 (HUC8) watersheds with greater than 50% forest cover, no impoundments above the streamflow gauges, at least four gauges per basin, and complete records back to 1950 in the Great Basin (number of HUC8 gauges = 6), Upper Colorado (16), Lower Colorado (5), and Rio Grande (4). Data generally show annual streamflow has been comparatively lower in more recent years compared to earlier decades. Panel (**c**) shows projected changes in suitable coldwater fish habitat in the Southeast under 3.6°F and 7.2°F warming air temperature over contemporary (2012) air temperature. Projections suggest suitable coldwater fish habitat will decline in the future as air temperatures increase. Figure credits: (a) adapted from Liu et al. 2022;[124] (b, c) USDA Forest Service.

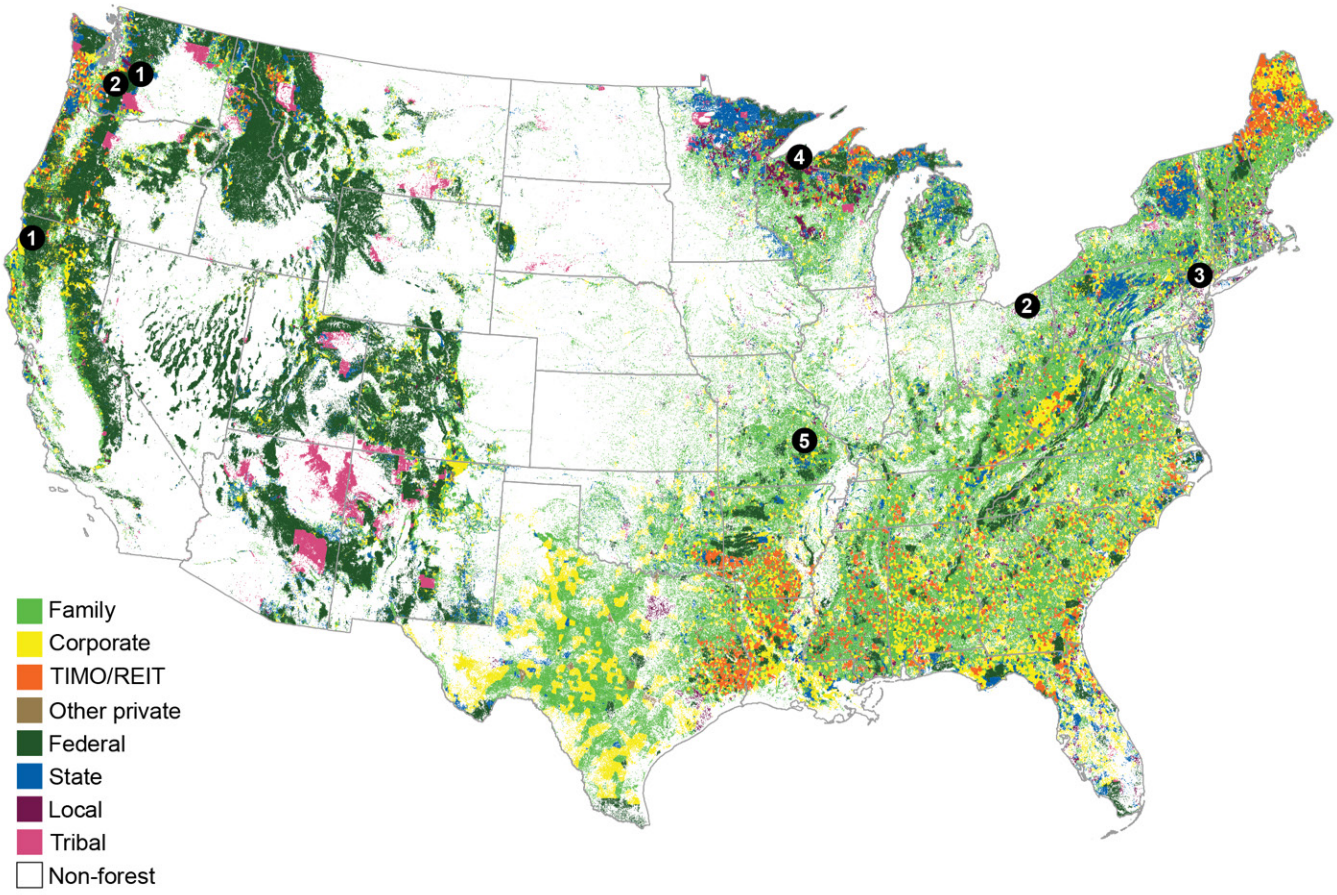
Key Message 7.3

Adaptation Actions Are Necessary for Maintaining Resilient Forest Ecosystems

Climate change creates challenges for natural resource managers charged with preserving the function, health, and productivity of forest ecosystems (*high confidence*). Forest landowners, managers, and policymakers working at local, state, Tribal, and federal levels are preparing for climate change through the development and implementation of vulnerability assessments and adaptation plans (*medium confidence*). Proactive adaptation of management strategies that create, maintain, and restore resilient forest ecosystems are critical to maintaining equitable provisioning of ecosystem services (*medium confidence*).

Proactive adaptation of forest management can help maintain the continued provisioning of ecosystem services from forests (e.g., Peterson and Halofsky 2018;[147] Voggesser et al. 2013[87]). Since 2017, the development of assessments, frameworks, and tools to guide adaptation in forests has accelerated. Climate change vulnerability assessments and adaptation plans for federal (e.g., Halofsky et al. 2016;[148] Timberlake and Schultz 2019[149]), state (Figure 31.1; e.g., Ontl et al. 2018;[150] PADEP 2021[151]), private,[152] and Tribal lands[91,153] have proliferated. Similarly, many guides and frameworks for adaptation have been introduced (e.g., Adaptation Partners 2023;[154] Schuurman et al. 2020[155]). Examples of implementation of adaptation practices in forests are now much more widespread (Figure 7.10; Table 7.1).

Climate Adaptation and Forest Ownership



Adaptation actions occur across many types of forest ownership and management in the United States.

Figure 7.10. Forests in the eastern US are mostly privately owned, whereas the majority of forests in the western US are federally managed. Climate change adaptation actions have been implemented in diverse forest ownership settings. The numbers on the map correspond to locations of adaptation examples listed in Table 7.1 (example 6 is not depicted as it focuses on Puerto Rico, which is not shown on the map). TIMO = timber investment management organization; REIT = real estate investment trust. These data are not available for Alaska, Hawai'i, the US Caribbean, or the US-Affiliated Pacific Islands. Adapted from Sass et al. 2020.[156]

Table 7.1. Examples of Climate Change Adaptation Actions in Forest Ecosystems

Map Location	Climate Change Effect	Adaptation Response	References and Resources
1	Longer wildfire season and increased area burned.	Thin forests and conduct prescribed and cultural burns to reduce the risk of high-severity wildfire and promote valued plants.	Long et al. 2021[157] Marks-Block et al. 2019[158] WA DNR 2020[159]
2	Species and genotypes may be maladapted to future climate.	Plant genotypes and species considered more tolerant of increased temperatures and changing disturbance regimes.	St. Clair et al. 2022[160] NIACS 2022[161] NIACS 2022[162]
3	Increasing temperatures and other stressors threaten urban forests.	Develop silvicultural techniques to maintain urban forests.	Piana et al. 2021[163] Piana et al. 2021[164] Pregitzer et al. 2019[165]
4	Climate change adaptation plans are not typically suited to the needs of Indigenous Peoples.	Develop a Tribal climate change adaptation menu to incorporate Tribal values and cultural considerations into climate adaptation planning.	Tribal Adaptation Menu Team 2019[166]
5	More frequent and severe flooding.	Relocate and restore recreation-related infrastructure in vulnerable floodplains.	NIACS 2022[167]
6	More intense hurricanes increasing downed and damaged trees.	Increase capacity to learn from disaster and manage vegetative debris in order to recover value and sequester carbon.	Álvarez-Berríos et al. 2021[168] Wiener et al. 2020[169]

Taking into account all lands and people improves climate change vulnerability assessments, because of the many federal, state, territorial, municipal, private, Tribal, and Indigenous management policies and practices governing forests. Adaptation options differ by region, ownership, and management objectives, reflecting differences in regional climate and ecology, management history, and local values. However, general principles for adaptation hold across geographies and ownerships and are consistent with the principles of sustainable forest management. For example, in drought-prone temperate forests, reducing tree densities increases resistance (the ability to remain largely unaltered by disturbance) and resilience (the ability to recover after disturbance) to bark beetles and drought[170,171] and, when combined with fuel reduction treatments (e.g., prescribed fire), resilience to wildfire.[145,146] In fire-prone forests, reintroducing low- to mixed-severity fire and incorporating Indigenous Knowledge into fire management can reduce the risk of high-severity wildfire and promote valued ecosystem services[172,173] (Table 7.1; KM 16.3). Promoting biological diversity is also a common adaptation strategy,[150] as forest areas of high diversity are better at maintaining ecosystem functions.[174] Increasing the diversity of functional traits, such as shade tolerance, seed size, specific leaf area, ability to resprout, and bark thickness, may give forests a better chance to adapt to climate-related disturbances.[174,175]

Opportunities to better integrate social considerations of climate-driven changes in forests and forest management are emerging, as socioecological vulnerability frameworks and assessments expand their treatment of social dimensions.[176,177] For example, assessments can consider ecological changes and altered ecosystem services in light of the socioeconomic characteristics (e.g., social vulnerability) and welfare of the beneficiaries of ecosystem services, including social capacity to adapt to novel conditions. Access to forests and associated ecosystem services, including recreation, differs from urban to rural settings and with socio-economic characteristics such as racial and ethnic identity. For example, Black landowners in the South face

a legacy of unequal access to forestry extension and management, as well as insecure property ownership and minimal economic return for land inherited without a will.[178] Environmental justice analyses can be used to consider access to forests, technical assistance for forest management, and ecosystem services, as well as hazardous occurrences such as wildfire smoke.[179,180]

Forest health and management are tied to socioeconomic well-being among Indigenous and Tribal Peoples, where stewardship of forest ecosystems is interrelated with cultural identity (KM 16.3).[181,182] Such perspectives lead to different adaptation options with emphasis on active management designed to maintain reciprocal relationships. For example, many Diné (Navajo) depend directly on the land for their livelihoods and cultural traditions, and forests provide social, cultural, spiritual, and economic resources. Under continued warming, substantial forest losses are projected for the Diné. Ambitious tree planting strategies have been proposed to offset these losses and meet future resource needs (e.g., for fuelwood; 50% of Diné households use wood as a primary heating source).[183]

Adapting reforestation practices, including where species are planted and which species and genotypes are planted, will facilitate adaptation to future climatic conditions. Assisted migration can help address the effects of climate change by promoting tree species and genotypes expected to survive future climates and disturbance regimes.[184] Assisted migration encompasses 1) assisted population migration within a species range, 2) assisted range expansion adjacent to a species range, and 3) assisted species migration that moves species far outside their range.[185] Specific guidance on assisted migration is rare, but tools such as hierarchical decision-making,[186] the Seedlot Selection Tool,[160] and the Managed Relocation Ecological Risk Assessment Tool[187] provide guidance.

Assisted migration and reforestation efforts are constrained by unreliable availability of climate-adapted seedling stock or other resources.[188] Adaptation interventions can focus on altering the exposure of forests to climate change or the demand for ecosystem services. Interventions include forest management that alters stand structures or composition, strengthening of disturbance response, and bolstering post-disturbance restoration.[189,190] Private forest owners' actions to adapt to climate change are socially, institutionally, and economically constrained (e.g., Andersson and Keskitalo 2018[191]); therefore, policy and market-based incentives have the potential to increase adaptation on private lands (e.g., Anderson et al. 2019[192]). Potential policies include regulations that require adaptation actions; subsidies (direct payments and tax reductions) that reduce private costs of actions or account for public benefits of private actions;[193] and taxes that increase the private costs of inaction or of actions that make forests less resilient to climate change (e.g., Hashida et al. 2020[194]). Given that future benefits from a private intervention are uncertain, subsidies (e.g., for hazardous fuels management) also reduce financial risks (e.g., Amacher et al. 2006[195]).

Effective implementation of climate adaptation requires working across landscapes with complex governances.[196] Equitable outcomes are enhanced by coproduction of knowledge (i.e., involving multiple knowledge sources and capacities from different groups of people) that determines expected risks, desired future benefits, and the capacity for implementing adaptation actions.[197]

Traceable Accounts

Process Description

Author selection centered on scientific expertise and ensuring that, to the extent possible, the author team represented a broad array of experiences. First, an outline of broad themes was developed by the chapter lead (CL) and federal coordinating lead author (CLA) based on review of previous assessments, a US Global Change Research Program (USGCRP) gap analysis, and new findings since the last National Climate Assessment.[11] The outline served as the basis for identifying the expertise necessary to complete the chapter. Next, the CL and CLA independently developed initial author lists following diversity criteria and guidance provided by USGCRP. It is important to note that prior to author selection, including the CL and CLA, the chapter was designated an all-federal-author chapter by the Federal Steering Committee, with the option to include non-federal authors as technical contributors. The CL and CLA relied heavily on the prepopulated list of individuals nominated through the USGCRP public call for authors to compile the initial author lists. The CL and CLA then worked through their initial lists of authors by chapter theme using the diversity criteria to arrive at the final list of chapter authors.

The author team met weekly to discuss chapter developments, comments, and timelines. Additional chapter authors and technical contributors were identified and added to increase depth and diversify perspectives. These decisions were informed by author team meetings, reviews and revisions, and comments received from US government agencies and the public. Consensus was built leveraging the specific expertise of chapter authors and by referring to the peer-reviewed literature, which was heavily weighted to articles published in the last five years. Engagement with the public occurred through a workshop held in January 2022 and opportunities for public review. Engagement with other chapters occurred through meetings among chapter leadership.

Key Message 7.1

Forests Are Increasingly Affected by Climate Change and Disturbances

Description of Evidence Base

Abundant peer-reviewed literature indicates that climate change has increased the frequency, spatial scale, and severity of some disturbances that drive forest change.[56,198,199] Notable examples include area burned by wildfires in the West,[200] area burned by large wildfires in the West,[13] and area burned at high severity in the West.[18] Over half (55%) of the changes in fuel aridity in western US forests are attributable directly to climate change,[12] and relationships between wildfire and climate (low precipitation/drought or interactions between temperature and precipitation) explain the trends and most of the variation in area burned.[14,15,200,201] Projections of future wildfire[14,202] indicate climatic drivers, and forest responses are expected to differ with forest type and fuels, with the potential for fuel feedbacks to eventually limit increases in area burned (Kitzberger et al. 2017,[203] but see Abatzoglou et al. 2021[16]). There is also strong and increasing evidence that warming is reducing overwintering mortality and increasing voltinism (number of generations) of some bark beetles,[26,29,63] resulting in large impacts, especially in the West, and expansions of geographic and host ranges in both the Northeast and West.[26,63] In the Southwest, exceptional drought has compromised host tree defenses, resulting in increased bark beetle impacts.[58,60,61,204] Despite well-described physical changes to forest fuels following bark beetle outbreaks, effects on wildfires are mixed. These contradictions are largely explained by the different metrics used to assess wildfires, time since the outbreak, the spatial scale of studies, and the confounding effects of fire weather and beetle impacts.[66] Pathogens, extreme weather events (hurricanes, wind, flooding), and sea level rise have less evidence supporting widespread connections

between disturbance and climate, in part because attribution is difficult for phenomena that occur rarely. Continued warming and regional changes in precipitation are expected to amplify interactions among disturbance agents and further alter forest ecosystem structure and function. Evidence for shifts in tree species ranges as affected by climate change is available for some areas;[205,206,207] however, understory species range shifts will depend on whether the canopy is affected.[49,208]

Major Uncertainties and Research Gaps

A major uncertainty is the role of climate-related disturbance in landscape transformation, or the permanent transition to a different vegetation type, perhaps non-forested. Projecting future forest changes and resulting effects on ecosystem services should be predicated on an ability to simulate and anticipate the (sometimes rapid) emergence of novel vegetation types. A key research gap is whether and how much management actions may alter climate-driven disturbance effects and resulting forest ecosystem trajectories. For example, differences in forest type and management history affect fuels available to fire and how climate changes alter their flammability or susceptibility to insects or other disturbances. As a result, forest-specific management may be capable of altering some or most of the projected climate effects, all other things being equal, primarily for wildfire. Another research gap is the ability to model the hydrological responses in forested watersheds under novel combinations of climate and disturbance.

Description of Confidence and Likelihood

The vast majority of the scientific literature on forest disturbance supports a *high confidence* statement for the role of climate-related disturbance in structuring forest ecosystems, although estimates of the strength of relationships between climate and disturbance vary with mechanisms and methods. However, the mechanisms by which disturbances interact and the degrees to which they will chronically or acutely affect forests differ greatly with the type and nature of the disturbance. For example, interactions between wildfire and bark beetles are well documented and may be amplified over time, whereas interactions between drought and pathogens are poorly understood. Disturbances can rapidly alter forest structure and dynamics, as well as other resource values (e.g., recreation) and socioeconomic conditions. It is *likely* that such dynamics will continue, but it is difficult to project how much they will resemble the dynamics with which we have experience. Therefore, *high confidence* exists that future disturbances will further alter forest structure and function.

Key Message 7.2

Climate Change Affects Ecosystem Services Provided by Forests

Description of Evidence Base

Abundant peer-reviewed literature underpins how climate change is affecting ecosystem services. Most research supports that increases in air temperature and changing precipitation patterns are reducing the capacity of US forests to sequester and store carbon, especially in the West.[3] There is also strong evidence that climate change is reducing snowpacks and decreasing water supplies in the West.[125] Stream temperatures are increasing in multiple regions, reducing coldwater fish habitat.[137,138] Increases in the frequency of large wildfires in the West reduce air and water quality[103,132,134,209,210] and, when combined with an expanding wildland–urban interface (WUI),[5] *likely* increase structure losses.

Climate change affects timber by increasing the area burned by wildfires[211] and by increasing the area affected by, and the severity of, bark beetle outbreaks,[26,58] leading to increased timber salvage and lower timber values. Beetle outbreaks have also lowered scenic beauty, property values, and property tax revenues for local governments in some areas.[100] Non-timber products in some parts of the US are increasingly

subjected to variable output, due to climate-related increases in disturbances and variability in temperatures and seasonality,[212] affecting benefits of cultural ecosystem services, particularly for Indigenous and Tribal Peoples.[90,213] For example, in the Midwest and Northeast, rising average winter temperatures and reduced snow depth have increased the severity of winter tick (*Dermacentor albipictus*) and brainworm (*Parelaphostrongylus tenuis*) infestations[214,215] in moose, increasing adult and calf mortality and reducing hunting opportunities.[216,217,218] Rising sea levels are leading to ghost forests, thereby changing recreation and affecting storm surge buffering capacity.[219,220] Sea level rise is also projected to exceed mangrove accretion rates in future decades, leading to loss of mangrove forests in many places.[38,39,40] In response to warmer winters, however, mangrove expansion is currently occurring along the US Gulf and Atlantic coasts, enhancing coastal protection from storms and rising seas, adding biomass carbon, improving pelican habitat, creating loss of coastal views, increasing insects, reducing fishing access, and reducing habitat for whooping cranes, an endangered species.[41] Skiing in undeveloped areas and motorized snow-based activities in the continental US are projected to be affected by climate change by midcentury, with effects varying by region, model scenario, and participation measure.[93,221]

Major Uncertainties and Research Gaps

Climate change effects on recreation values are uncertain because human values change over time and because overall effects will depend on how temperature and precipitation patterns change across forested landscapes. Furthermore, imprecise information on historical recreation activities has led to a lack of statistical significances for quantitative estimates of how climate may be affecting particular activities. Research gaps exist regarding the effects of climate change on cultural goods and services important to Indigenous and Tribal Peoples in the US.

Description of Confidence and Likelihood

Recent research provides ample evidence of the direct and indirect effects of climate change on forest ecosystem services. There is *high confidence* that multiple ecosystem services are being impacted by climate change, including coldwater fishing, multiple recreation activities, amenities from coastal forests lost to rising seas, Indigenous forest values, consumptive and nonconsumptive wildlife provisioning, and many nontimber forest products. There is *high confidence* that climate change is affecting forest carbon sequestration; the provisioning of clean water from forests; the occurrence of wildfires that destroy structures, alter habitats, and increase $PM_{2.5}$ concentrations in the atmosphere; and snowpacks in the West and Northeast. There is *medium confidence* that climate change is changing the availability of water-based and snow-based recreation. The capacity of forests to continue providing ecosystem services will be determined, in part, by changes in society and how those changes interact with future climate effects (*likely, high confidence*).

Key Message 7.3

Adaptation Actions Are Necessary for Maintaining Resilient Forest Ecosystems

Description of Evidence Base

Climate change vulnerability assessments provide the basis for adaptation, and there are many examples of vulnerability assessments that have been conducted for a variety of forest landowners and managers in recent years. Although frameworks and examples of adaptation planning are still more numerous than adaptation actions, the recent literature contains an increasing number of adaptation actions implemented to increase forest resistance and resilience to climate change (Table 7.1). Research on climate change effects and adaptation efforts increasingly draws on coproduction, iterative, and collaborative processes that combine different types of knowledge and participants to produce effective climate adaptation science.[222]

Although considering local context and management objectives is critical in identifying climate change adaptation options, there are general principles applicable across forest types. Adaptation principles that receive strong support in the scientific literature include promoting diversity, modifying planting practices, implementing assisted migration, and increasing resilience to disturbance. A mixture of tree species and functional traits[223] in a forest stand increases the likelihood that disturbances, such as insect and disease outbreaks, will not result in complete stand mortality; that forests will be better able to withstand changing environmental conditions; and that multiple ecosystem services can be provided.[174,224] Strong and increasing evidence exists for lowering stand density in many fire-prone forest types to 1) increase resistance and resilience to disturbances, including droughts, bark beetles, and wildfires;[145,146,157,170,225] and 2) improve residual tree growth by decreasing fuel loads, decreasing tree competition, and increasing water availability.[225,226,227]

Major Uncertainties and Research Gaps

Identification of climate change adaptation actions is based on our current understanding of ecosystem function and how management actions affect ecosystem function. However, understanding of the effectiveness of climate change adaptation actions is limited by a lack of long-term monitoring over several decades. Future monitoring will be critical for evaluating the effectiveness of adaptation actions in different contexts, especially because interactions among multiple disturbances could result in unexpected effects on ecosystems and their response to adaptation actions. Implementation of adaptation actions is still in the relatively early stages, and barriers to adaptation implementation are expected to persist, limiting the future pace, scale, and effectiveness of adaptation.

Description of Confidence and Likelihood

There is *high confidence* that changes in climate over the last several decades are already affecting the ability of forest owners and managers to meet management objectives. This is primarily because of the increasing extent of severe disturbances, primarily wildfires, bark beetle outbreaks in the West, and storms in coastal locations in the East. This is based on the proliferation of peer-reviewed literature to support climate-informed management and planning, as well as various guidelines and sources of adaptation options developed by agencies and non-governmental organizations. Based on understanding of forest ecosystems and effects of management actions, there is *medium confidence* that adaptation actions will be effective in helping maintain the provisioning of ecosystem services. Continued monitoring is needed to assess the effectiveness of adaptation actions.

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Fifth National Climate Assessment: Chapter 8

Ecosystems, Ecosystem Services, and Biodiversity



Chapter 8. Ecosystems, Ecosystem Services, and Biodiversity

Authors and Contributors

Federal Coordinating Lead Author

Shawn L. Carter, US Geological Survey, National Climate Adaptation Science Center

Chapter Lead Author

Pamela D. McElwee, Rutgers University

Agency Chapter Lead Authors

Kimberly J. W. Hyde, NOAA Fisheries, Northeast Fisheries Science Center

Jordan M. West, US Environmental Protection Agency, Office of Research and Development

Chapter Authors

Kofi Akamani, Southern Illinois University Carbondale

Amanda L. Babson, US National Park Service

Gillian Bowser, Colorado State University

John B. Bradford, US Geological Survey, Southwest Biological Science Center

Jennifer K. Costanza, USDA Forest Service

Theresa M. Crimmins, University of Arizona, USA National Phenology Network

Sarah C. Goslee, USDA Agricultural Research Service

Stephen K. Hamilton, Cary Institute of Ecosystem Studies

Brian Helmuth, Northeastern University

Serra Hoagland, USDA Forest Service

Fushcia-Ann E. Hoover, University of North Carolina at Charlotte

Mary E. Hunsicker, NOAA Fisheries, Northwest Fisheries Science Center

Roxolana Kashuba, US Environmental Protection Agency

Seth A. Moore, Grand Portage Band of Lake Superior Chippewa

Roldan C. Muñoz, NOAA Fisheries, Southeast Fisheries Science Center

Gyami Shrestha, Lynker

Maria Uriarte, Columbia University

Jennifer L. Wilkening, US Fish and Wildlife Service

Technical Contributors

Nazia N. Arbab, Rutgers University

Danielle Cholewiak, NOAA Fisheries, Northeast Fisheries Science Center

Pranay Kumar, Rutgers University

Victor O. Leshyk, Northern Arizona University

Katherine C. Malpeli, US Geological Survey, National Climate Adaptation Science Center

Richard S. Ostfeld, Cary Institute of Ecosystem Studies

GraceAnne K. Piselli, Northeastern University

José R. Ramírez-Garofalo, Rutgers University

Edward A.G. Schuur, Northern Arizona University

Jacquelyn Veatch, Rutgers University

Sarah Whipple, Colorado State University

Sauvanithi Yupho, Rutgers University, Department of Geography

Review Editor

Abigail York, Arizona State University

Cover Art

Taelyn B.

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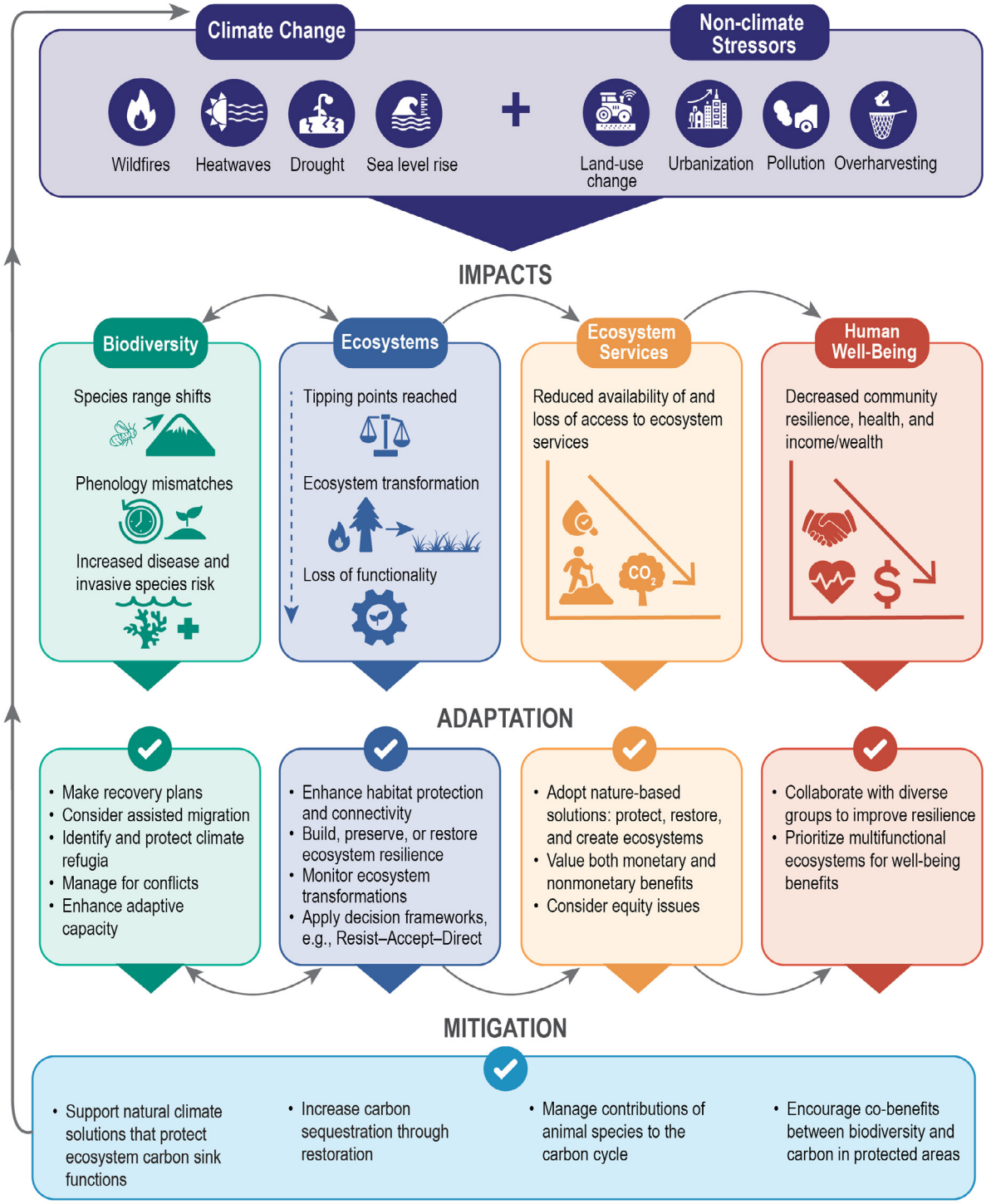
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Introduction

Human well-being is dependent on natural and managed ecosystems, which provide crucial functions and resources for nearly everything we eat, make, and do.[1] Clean water and air, soils and nutrients for food production, timber for construction, and other supplies and services we depend on all come from nature. But many ecosystems are increasingly facing climate risks and impacts that alter ecological processes and functions and affect species across all levels of the food web. These changes in turn can result in reduced biodiversity and diminished ecosystem services (the benefits received from natural systems; Figure 8.1).[2,3] Relationships between humans and ecosystems, such as the kinship values that many Black, Indigenous and Tribal communities experience with regard to nature, are also endangered by these changes.[4,5]

Climate Change and Ecosystems, Biodiversity, and Ecosystem Services

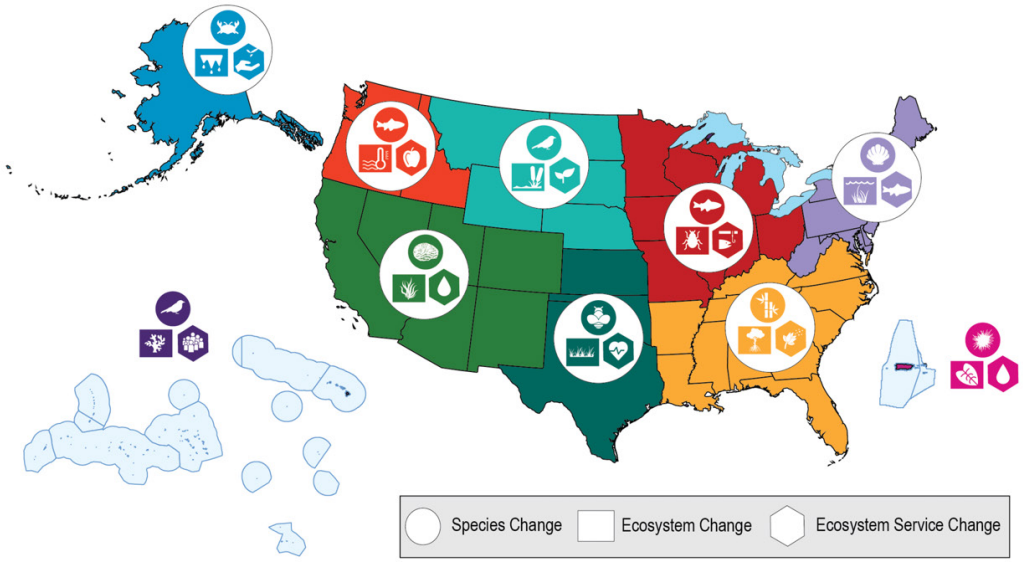


Climate and non-climate stressors together affect biodiversity, ecosystems, and the services they provide.

Figure 8.1. Species and ecosystems respond to pressures in different ways, such as shifting their locations or transforming into new, often degraded systems less able to provide ecosystem services.[6] Adaptation measures can help species and ecosystems cope with some climate impacts but are not always going to be effective or feasible, requiring increasingly difficult decisions on what resources to prioritize and what changes to accept.[7] Adapted from Lipton et al. 2018.[8]

Climate change impacts are already seen in the deterioration of ecosystem functions, as well as in changes in marine and terrestrial primary productivity (growth of plants and algae) and the balance between primary production and respiration (i.e., carbon balances).[2] Ecosystem degradation increases risks to human populations, such as in coastal areas where loss of wetlands increases damage from storms (KM 9.2). Other observed impacts include range shifts as species expand into new regions or disappear from unfavorable areas, altered timing of seasonal and life-cycle events, increased mortality and localized extinctions, and spread of diseases and invasive species (Figure 8.2).[9,10] These risks are projected to grow with additional degrees of warming (Figure 8.3),[11,12] as well as with increased atmospheric carbon dioxide, which contributes to the acidification of marine ecosystems (KM 10.1).[13]

Regional Impacts

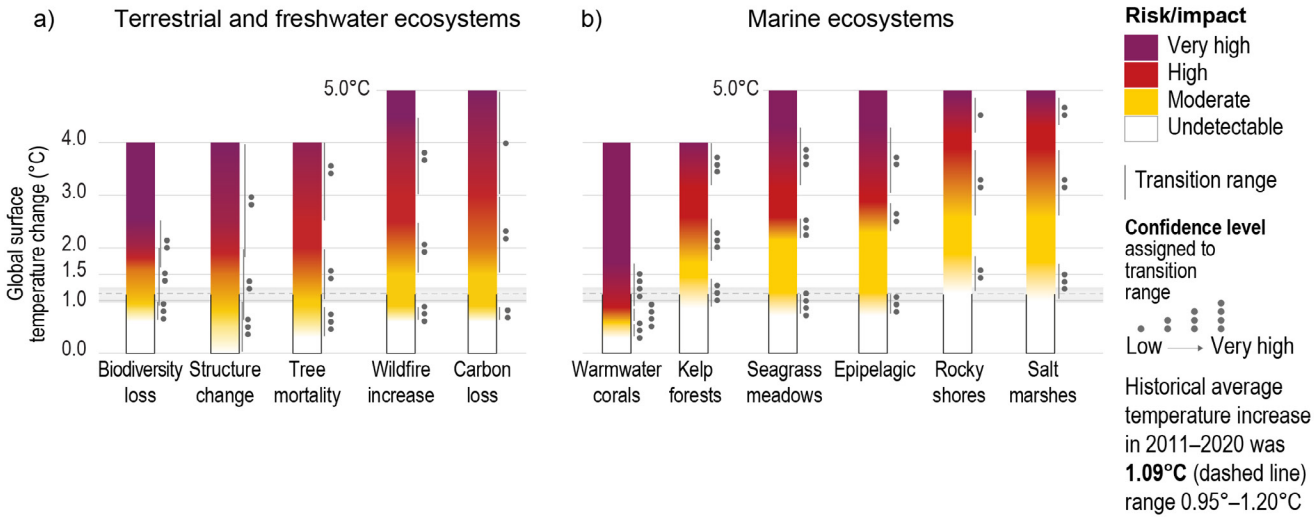


NCA Region	Species Change	Ecosystem Change	Ecosystem Service Change
Alaska	Commercial crab decline (KM 29.5)	Permafrost thaw and erosion (KM 29.5)	Cultural identity loss (Box 29.3)
Northern Great Plains	Grassland bird decline (KM 25.2)	Prairie wetlands threats (Box 25.2)	Delayed harvest of culturally important plants (KM 25.3)
Midwest	Brook trout decline (KM 24.2)	Increased agricultural pests (KM 24.1)	Recreational lake ice loss (Figure 24.6)
Northeast	Sea scallop decline (KM 21.2)	Coastal habitat loss (KM 21.2)	Impacts to fishing communities (KM 21.2)
Southeast	Rivercane loss (Box 22.3)	Coastal forest degradation (KM 22.1)	Increased pollen (KM 22.2)
US Caribbean	Sargassum seaweed increase (KM 23.4)	Tropical forest productivity declines (KM 23.2)	Reduction in water availability (KM 23.3)
Southern Great Plains	Pollinator disruptions (KM 26.2)	Decreased rangeland health (KM 26.1)	Extreme heat affecting human health (KM 26.3)
Southwest	Red abalone critically endangered (KM 28.2)	Kelp forest decline (KM 28.2)	Reduced water availability (KM 28.1)
Hawai'i and US-Affiliated Pacific Islands	Avian extinctions (KM 30.4)	Coral reef loss (KM 30.1)	Cultural practices threats (Box 30.6)
Northwest	Invasive bass increase (KM 27.2)	Marine heatwaves (KM 27.2)	Reduced crop yields (KM 27.3)

All US regions are experiencing impacts of climate change on species, ecosystems, and ecosystem services.

Figure 8.2. Regional examples show the wide range of potential ecosystem impacts and their socioeconomic ramifications. Some changes may be occurring in more than one region (e.g., loss of coral reefs in both Hawai'i and the US-Affiliated Pacific Islands [USAPI] and in the US Caribbean). Figure credit: Rutgers University and USGS.

Ecosystem Impacts and Risks



Ecosystem impacts and risks increase at higher levels of global warming.

Figure 8.3. As global surface temperatures increase relative to the preindustrial period (1850–1900), risks to ecosystems, such as changes in structure and function, become more acute beyond the 1.09°C (1.96°F) of warming that has already occurred (light gray dashed line). Maximum risk is reached below 4°C (7.2°F) of warming in some cases and between 4° and 5°C (9°F) in others. Very high risks to sensitive ecosystems, such as coral reefs, are anticipated above 2°C (3.6°F) and will be difficult to reverse. Adapted with permission from Figure SPM.3 in IPCC 2022.[2]

Ecosystem-based and climate-informed management that anticipates and adapts to changes can limit damage and increase resilience of ecosystems (Figure 6.7; KM 6.2).[14] Strategies include restoration, habitat protection and connectivity, assisted migration, and adaptive management.[15,16] However, there are limits to adaptive management, particularly for unique systems and species and the humans who depend on them.[2] For example, adaptive management may not be able to keep up with rising sea levels that submerge coastal communities and ecosystems (KM 9.1) or extreme heat that is intolerable to humans or other organisms (KM 15.1).

This chapter focuses on risks to terrestrial, freshwater, and marine ecosystems; more details on the following ecosystems can be found as noted: land (Ch. 6), forests (Ch. 7), coasts (Ch. 9), oceans (Ch. 10), and agroecosystems (Ch. 11).

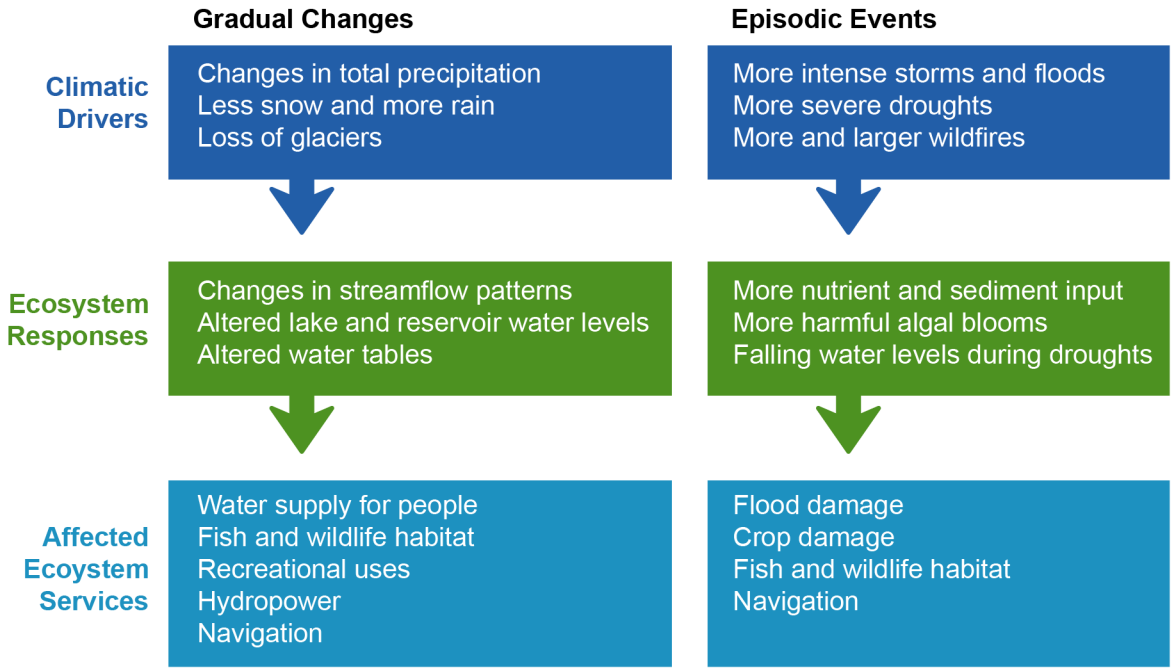
Key Message 8.1

Change Is Driving Rapid Ecosystem Transformations

Climate change, together with other stressors, is driving transformational changes in ecosystems, including loss and conversion to other states, and changes in productivity (*very likely*, *high confidence*). These changes have serious implications for human well-being (*very likely*, *high confidence*). Many types of extreme events are increasing in frequency and/or severity and can trigger abrupt ecosystem changes (*medium confidence*). Adaptive governance frameworks, including adaptive management, combined with monitoring can help to prepare for, respond to, and alleviate climate change impacts, as well as build resilience for the future (*medium confidence*).

Ecosystem changes can be driven by physical factors (e.g., thermal stress), biological responses (e.g., changing ranges), or both, often interacting with stressors from human activities. Multiple stressors, both gradual and episodic, can have complex interactive or amplifying effects on ecosystems (Figure 8.4);[17,18] for example, severe hurricanes can heighten forest vulnerability to drought and/or fire.[19,20]

Amplifying Climate Change Effects on Watersheds

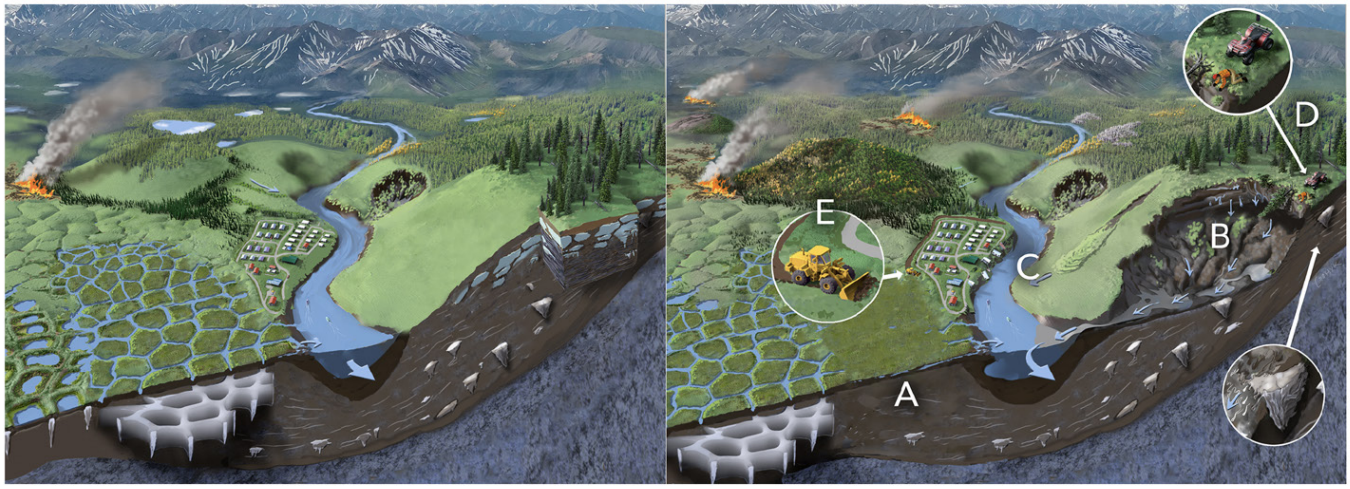


Climate effects on watersheds exemplify the amplifying impacts of gradual and episodic stressors.

Figure 8.4. Both gradual and episodic (short-lived) climatic drivers alter the transport of water, nutrients, and sediments from terrestrial watersheds to downstream water bodies. These drivers affect aquatic ecology and ecosystem services throughout the hydrological system, even in areas distant from drivers of change (e.g., more intense rainfall leading to leaching of fertilizers that stimulate harmful algal blooms downstream).[21] The frequency and intensity of episodic extreme events is projected to increase (KM 2.2), raising risks for many species (Figure 8.10). Figure credit: Cary Institute of Ecosystem Studies.

Many ecosystems are at increased risk of ecosystem tipping points (where rapid and unpredictable conversions to new states occur),[22] although it is difficult to predict how, where, and when these changes will occur.[23,24] Transformative changes in the composition, structure, function, and other properties of ecosystems result in a new stable state, or regime, with a different combination of species and communities, often resulting in reduced biodiversity and ecosystem services.[25,26] Restoring an ecosystem may be difficult or even impossible if a critical threshold or tipping point is crossed and a different system emerges, because changing or restoring the drivers that led to the altered state may not result in a return to the original state (Figure 8.5).[27]

Tipping Points and Regime Changes

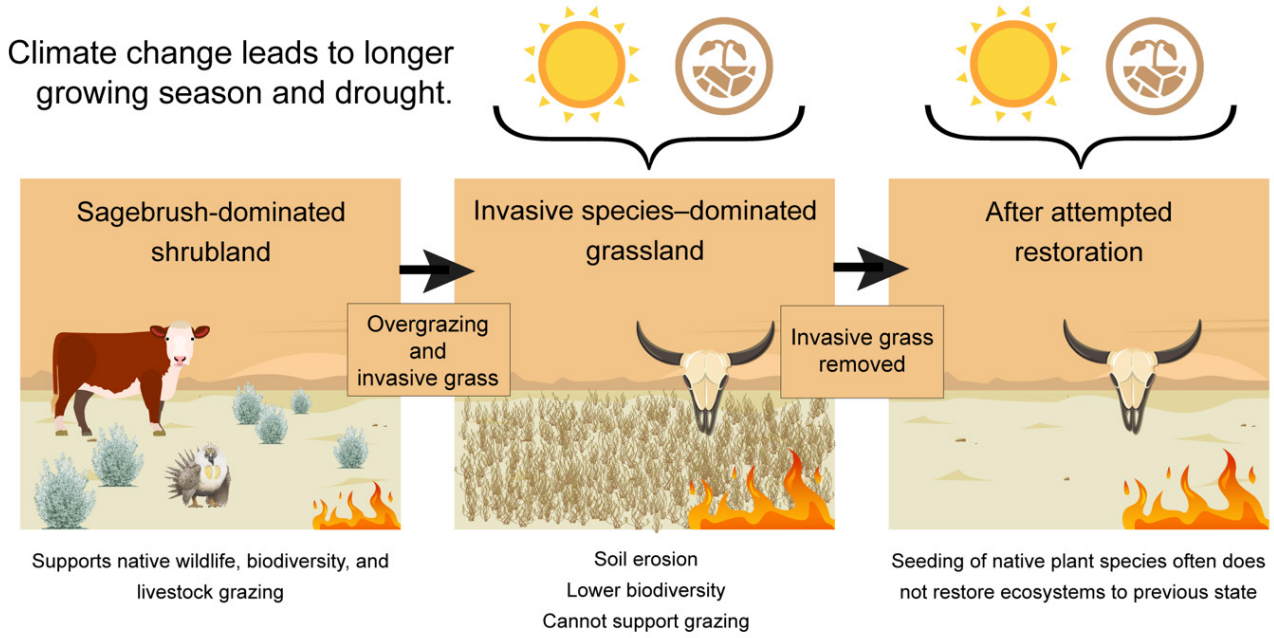


The Arctic faces substantial impacts from thawing permafrost that cannot be reversed.

Figure 8.5. Thawing of permafrost can cause irreversible tipping points in Arctic landscapes, transforming intact ecosystems (**left**) to severely altered ones (**right**), with impacts on people. A warming climate and fires lead to melting ground ice. Arctic and boreal forests contain permafrost soils with excess ice (more than is contained in soil pores), which form 3D networks in the ground. With warming, this ground ice can melt and the ground surface collapses (**A**). Fires, a natural part of the boreal disturbance cycle, are increasing in extent, frequency, and severity. Melting ice can lead to accumulation of water in ponds, lakes, and wetlands, but continued thawing can cause lakes to drain. Permafrost can also thaw abruptly, causing thaw slumps and bank failures (**B**). These geomorphological changes impact human infrastructure (**C**) and access to the land (**D**). Other risks (not pictured) include chemical and potentially disease mobilization that can threaten human health and ecosystems.[28,29] Human adaptation strategies to permafrost thaw include installing firebreaks around infrastructure (E). Adapted from Schuur et al. 2022[30] [CC BY 4.0].

Ecosystem changes can be gradual or relatively abrupt[31] and depend in part on ecosystem characteristics and key species.[32] Ecosystems with immobile or long-lived species such as corals or trees can often exhibit abrupt responses because they have limited capacity to keep pace.[33,34,35] Ecosystems with higher biodiversity have more species interactions and often exhibit slow changes at first followed by abrupt shifts.[15] Multiple stressors can lead to synergistic effects and trigger abrupt changes.[36] Examples include the co-occurrence of extreme heat, drought, and invasive grasses (Figure 8.6)[22] or wildfires followed by insect infestations (or vice versa; Focus on Western Wildfires).

Abrupt Changes in Ecosystem State

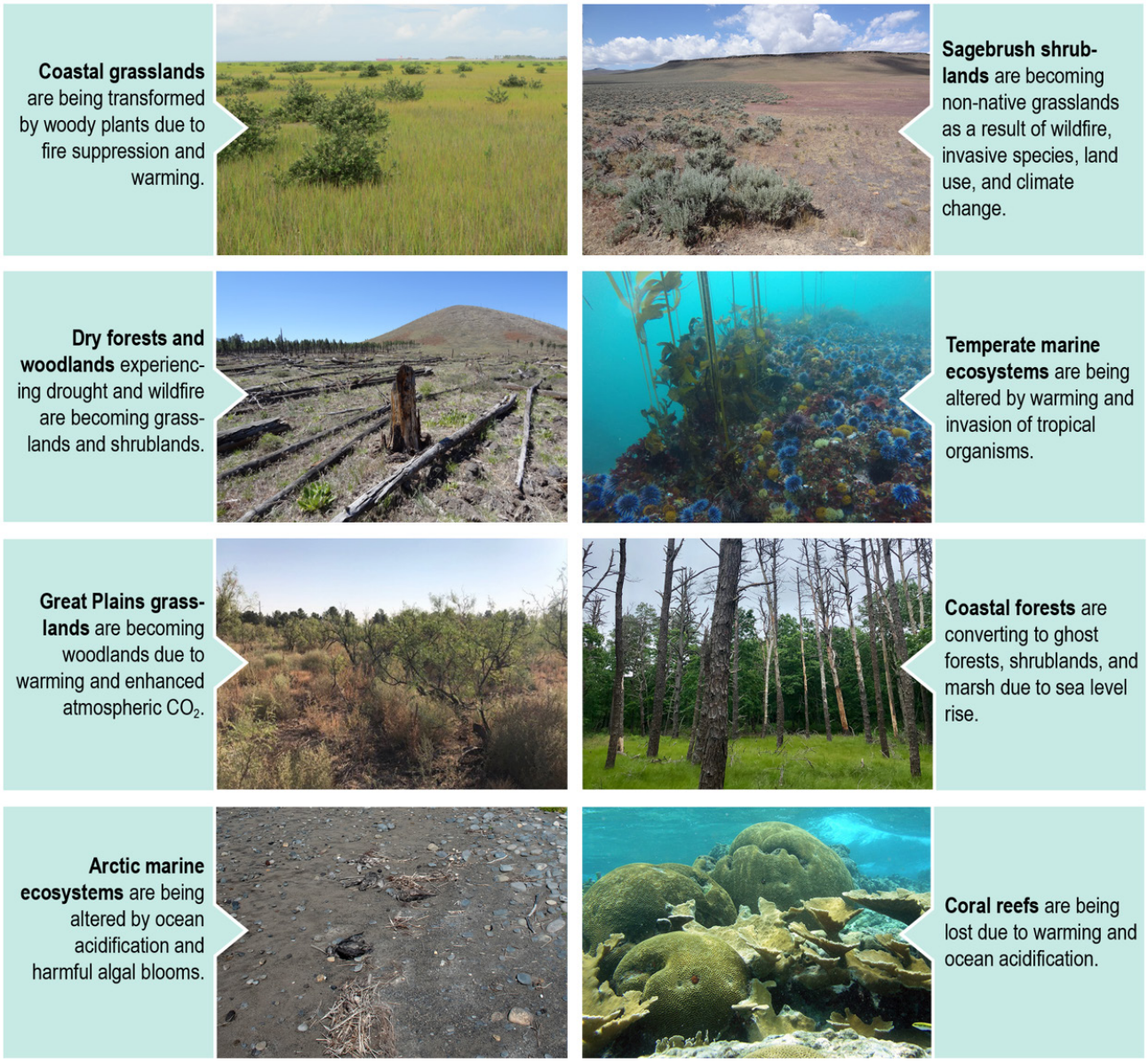


Climate change interacts with other stressors to cause synergistic effects, and resulting ecosystem changes can be abrupt and difficult to reverse.

Figure 8.6. In the western US, drought and longer, hotter growing seasons combined with invasive grasses and overgrazing have transformed sagebrush shrublands past a tipping point into annual grasslands that experience more frequent wildfires and no longer support native biodiversity and livestock grazing. Removing invasive grasses and seeding with native plants often does not restore the original shrubland ecosystem.[37] Adapted from Foley et al. 2015[38] [CC BY 4.0].

Vulnerability of ecosystems to climate change depends on exposure to the physical drivers of change and characteristics that affect species' sensitivity and capacity to adapt.[39] Examples of vulnerable ecosystems experiencing transformation are increasingly common (Figure 8.7). There is evidence that ecosystems with higher biodiversity are more resilient in the face of climate change,[40,41] indicating that better protection and reduced fragmentation and degradation of ecosystems are potential climate-adaptation strategies.[42]

Unique and Vulnerable Ecosystems



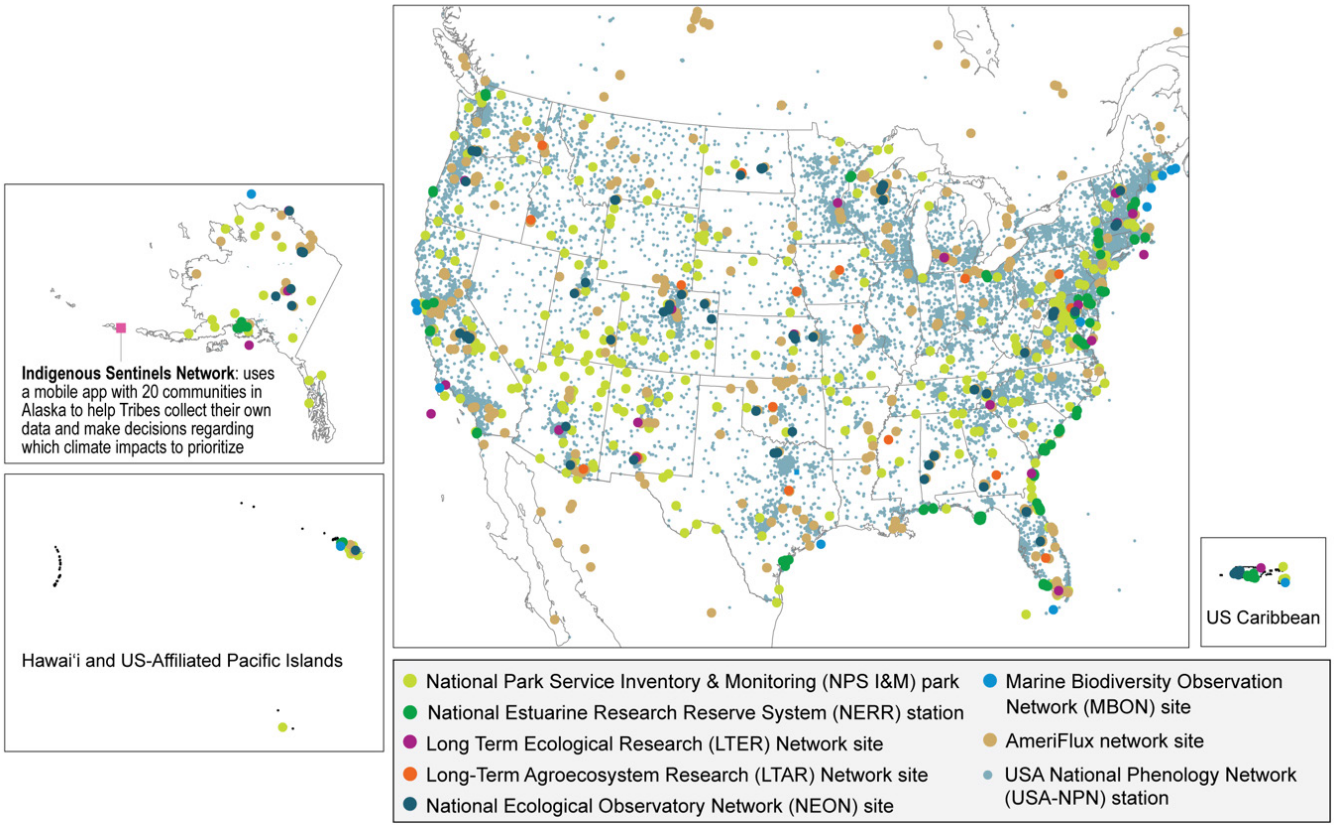
Transformations to ecosystems are already noticeable and widespread.

Figure 8.7. There are numerous and widespread examples of ecosystems transforming to altered states, with complex drivers and outcomes.[22,43,44,45,46] Climate-driven ecological transformations are occurring in all regions of the US and often negatively impact the services these ecosystems provide, including regulation of carbon and water cycles, wildlife habitat, and recreation. Figure credit: USDA Forest Service, USGS, and NOAA Fisheries. Photo credits (clockwise from top right): John Bradford, USGS; Steve Lonhart/NOAA; ©Elizabeth-Ann Jamison; Ilsa B. Kuffner, USGS; Sarah K. Schoen, USGS; ©Nicholas Smith; John Bradford, USGS; ©Anna Armitage.

Monitoring Transformations

Identifying and monitoring species or ecosystem traits that provide early warnings of vulnerability, system-wide decline, or tipping points can assist in reducing risks.[26,47,48,49] Numerous long-term monitoring networks (Figure 8.8) have been established in recent decades in direct response to climate and other changes.[27,50] Community-led ("citizen") science efforts such as iNaturalist[51] and the USA National Phenology Network,[52] alongside community-based monitoring networks[53] and Indigenous Knowledge holders (KM 16.3)[54] also collect observations across large areas[55] and have helped detect altered species distributions, abundances, and phenologies.[56,57,58]

Monitoring Ecosystem Changes



Monitoring programs are critically important for observing and projecting trends in resilience, species invasions, range shifts, declines, and extinctions.

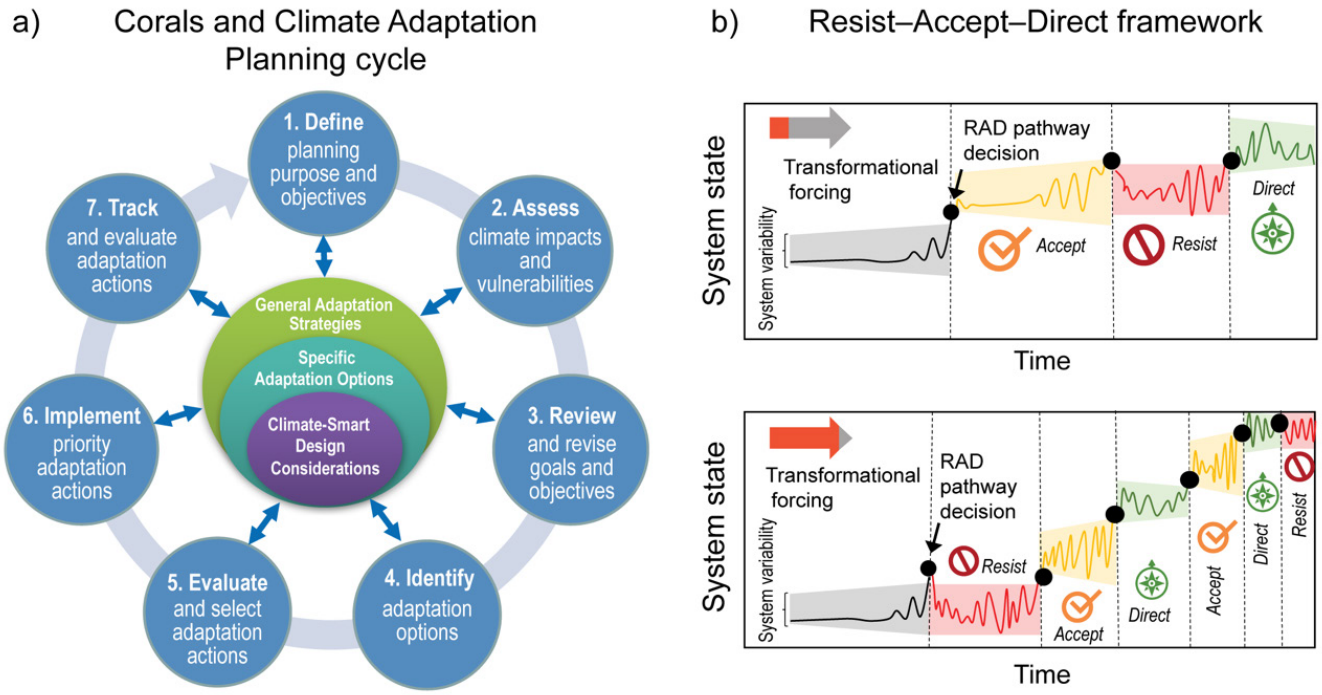
Figure 8.8. Federally operated networks (NPS I&M, NERR) and other long-term networks (LTER, LTAR, NEON, MBON, AmeriFlux) provide consistent and permanent observations at limited sites, whereas volunteer networks (USA-NPN, Indigenous Sentinels) offer more opportunistic observations across a wider landscape. Together, these networks provide critical data for understanding species and ecosystem changes, although gaps in coverage remain. Figure credit: Lynker and USGS.

Addressing Risks and Managing for Change

Climate change and other disturbances that transform ecosystems create growing management challenges.[14,59] Building, preserving, or restoring ecosystems is often the most practical and effective resilience strategy;[60,61] however, ecosystem transformation may still be inevitable.[62] Conventional resource management approaches are often ill-suited for managing uncertainties and related trade-offs.[63,64] In contrast, adaptive management iteratively plans, implements, and modifies strategies for managing resources under uncertainty. Successful adaptive management requires an overarching adaptive governance approach that provides institutional structures and decision-making processes for coordinating efforts across scales,[65] managing uncertainties and conflicts,[66,67] mobilizing diverse knowledges, and addressing stakeholder interests.[68,69,70]

Decision frameworks designed to anticipate ecosystem transformation can advance adaptative management processes (Figure 8.9).[71] As one example, the Resist–Accept–Direct (RAD) framework helps identify conditions where ecosystem management can resist a trajectory of change, accept change, or direct change toward desired future conditions (Figure 8.9b).[62,72] To engage the "direct" in their RAD planning, Tetlin National Wildlife Refuge in Alaska is combining scenarios, adaptive management, and adaptive pathway planning to engage managers and stakeholders to explore potential transformations, with one focus specifically on subsistence hunting.[73]

Adaptation and Transformation Planning Frameworks



Decision frameworks can help plan for the potential transformation of ecosystems.

Figure 8.9. Two examples of adaptive decision frameworks are the Corals and Climate Adaptation Planning cycle (**a**) and the Resist–Accept–Direct (RAD) framework (**b**). In (a), users are guided through assessment and design considerations to adjust climate-smart management interventions. In (b), the current ecosystem (gray) is affected by either moderate or strong transformational forcing that drives decisions (black dots) to resist (red time periods), accept (yellow time periods), and direct (green time periods) the trajectory of change. (a) Adapted from West et al. 2017, 2018[74,75] [CC BY 4.0]; (b) adapted from Lynch et al. 2022.[72]

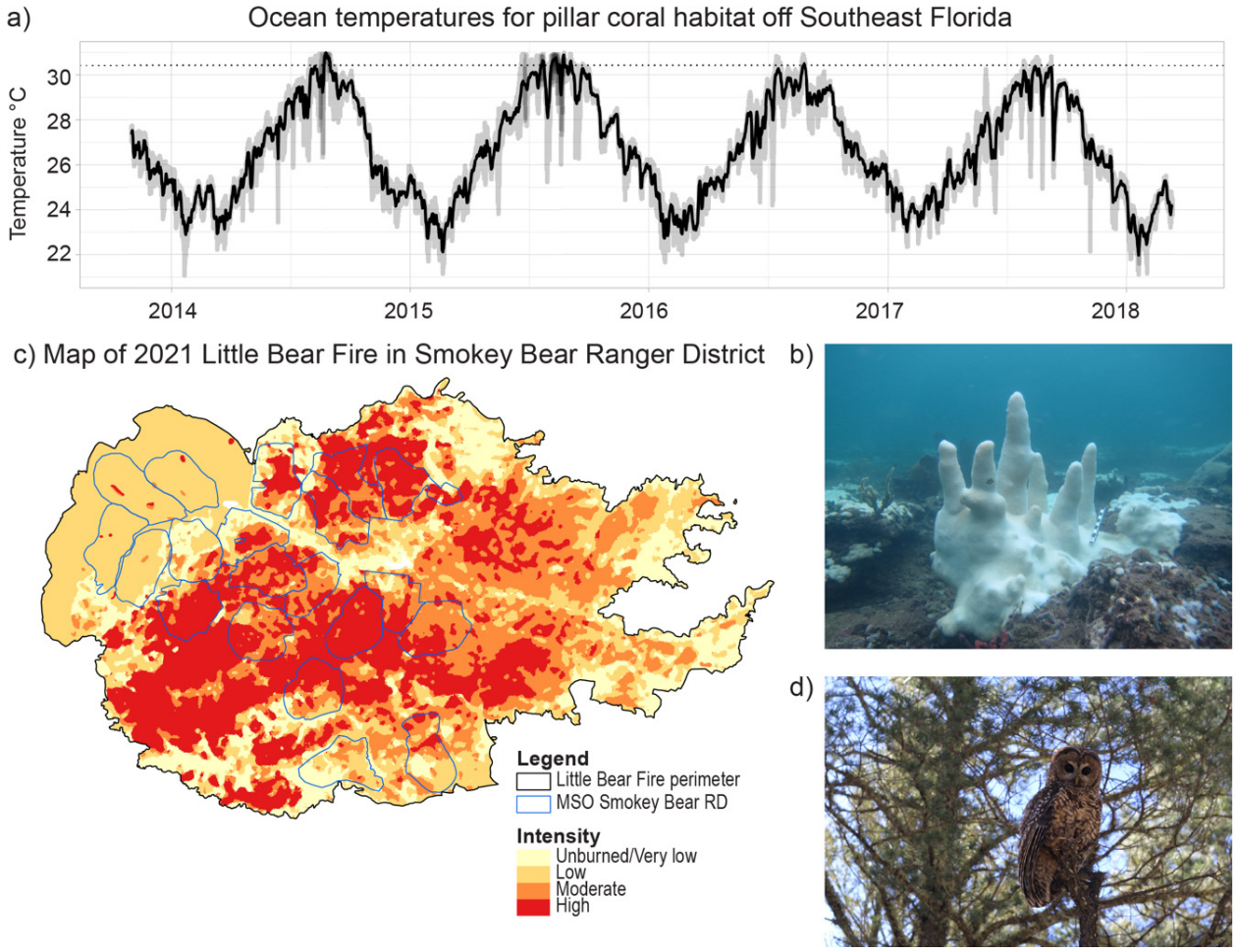
Key Message 8.2

Species Changes and Biodiversity Loss Are Accelerating

The interaction of climate change with other stressors is causing biodiversity loss, changes in species distributions and life cycles, and increasing impacts from invasive species and diseases, all of which have economic and social consequences (*very likely*, *high confidence*). Future responses of species and populations will depend on the magnitude and timing of changes, coupled with the differential sensitivity of organisms; species that cannot easily relocate or are highly temperature sensitive may face heightened extinction risks (*very likely*, *high confidence*). Identification of risks (e.g., extreme events) will help prioritize species and locations for protection and improve options for management (*very likely*, *high confidence*).

Climate-related stressors and other drivers of global change, such as land-use change, habitat destruction, and overexploitation, can create significant biodiversity changes and losses (Figure 8.1).[76,77] Even short-term extreme events such as heatwaves[78,79,80] can generate significant species impacts. For example, coral reefs are threatened by cumulative impacts of ocean warming and acidification, marine heatwaves resulting in bleaching and higher susceptibility to diseases, increasingly powerful tropical cyclones causing loss of structural complexity, hypoxia (low oxygen) events, overfishing, and pollution (Figure 8.10a, b; Box 10.1; KMs 9.2, 10.1).[81,82,83,84,85,86] Similarly, wildfires (Focus on Western Wildfires)[87] can create risks for some species both directly (Figure 8.10c, d) and indirectly through longer-term habitat changes.[88]

Extreme Event Impacts



Short-term extreme events can have severe impacts on threatened species.

Figure 8.10. Two examples of such impacts are as follows. (**a**) High water temperatures off Southeast Florida exceeded the maximum average monthly temperature (horizonal line in time series) in 2014–2015, resulting in severe bleaching of (**b**) pillar coral (*Dendrogyra cylindrus*) colonies and subsequent disease and death of all individuals. (**c**) Wildfires impacted more than 75% of breeding pairs (blue polygons) of (**d**) Mexican spotted owl (MSO; *Strix occidentalis lucida*) in Smokey Bear Ranger District, New Mexico, in 2012. Figure credits: (a) adapted from Jones et al. 2021[89] [CC BY 4.0]; (c) USDA Forest Service, NOAA Fisheries, and NOAA NCEI. Photo credits: (b) ©David Gilliam, Nova Southeastern University; (d) ©Serra J. Hoagland, USDA Forest Service.

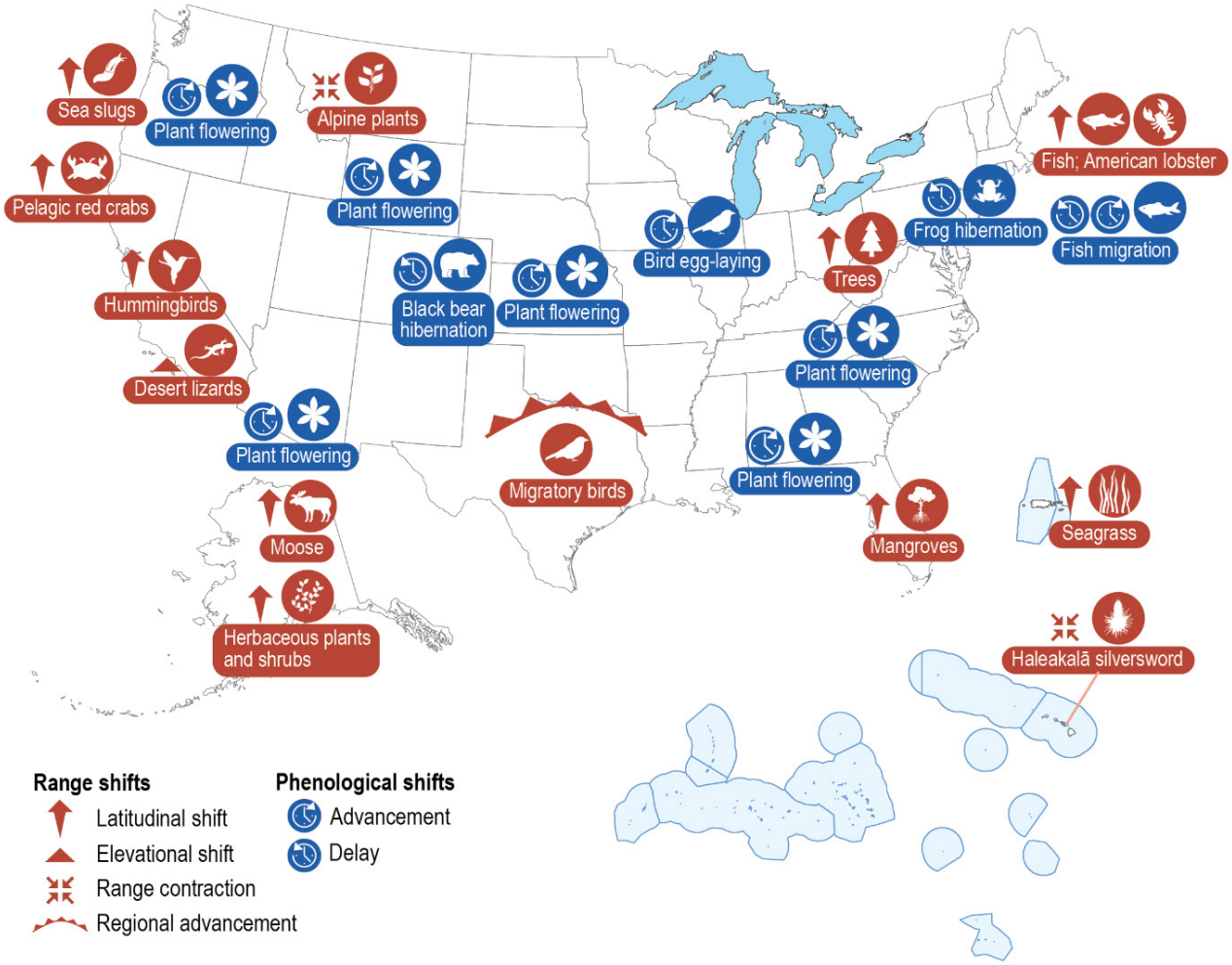
Changes in Phenology

Compounding the responses of species to extreme events, the timing of seasonal events such as leaf-out, flowering, migration, spawning, phytoplankton blooms, and egg hatching is changing in response to rising winter and spring temperatures and to the altered timing and amount of snowmelt and rainfall (Figures 8.8, A4.13).[58,90,91,92] Changes include earlier flowering and maturity in agricultural crops that affect planting and harvest times,[93,94,95,96,97] longer and more intense allergy seasons (KM 14.4),[98] and increased pest activity.[99,100] Changes are most pronounced at high latitudes and elevations and in urbanized areas.[101,102] Phenological mismatches emerge when the timing of activities in interacting species changes at different rates, such as food availability shifting to no longer match a dependent organism's needs.[103,104] Phenological changes are also impacting seasonal carbon cycling[105] and increasing vulnerability to spring frost damage (App. 4).[106] There are significant economic and social impacts of these changes, including tourism impacts and loss of culturally important species.[107,108]

Range Shifts

Elevational and latitudinal range shifts driven by climate change have already occurred for multiple species (Figure 8.11),[109,110,111] with range shifts of marine species more responsive and greater in magnitude than terrestrial ones (KM 10.1; Figure A4.12).[112] Mountaintop ranges are shrinking as species shift upslope, with high-elevation ones highly vulnerable.[113,114] Milder winters and warmer growing seasons are expected to expand ranges for some species.[115,116]

Observed Range Shifts and Changes in Phenology

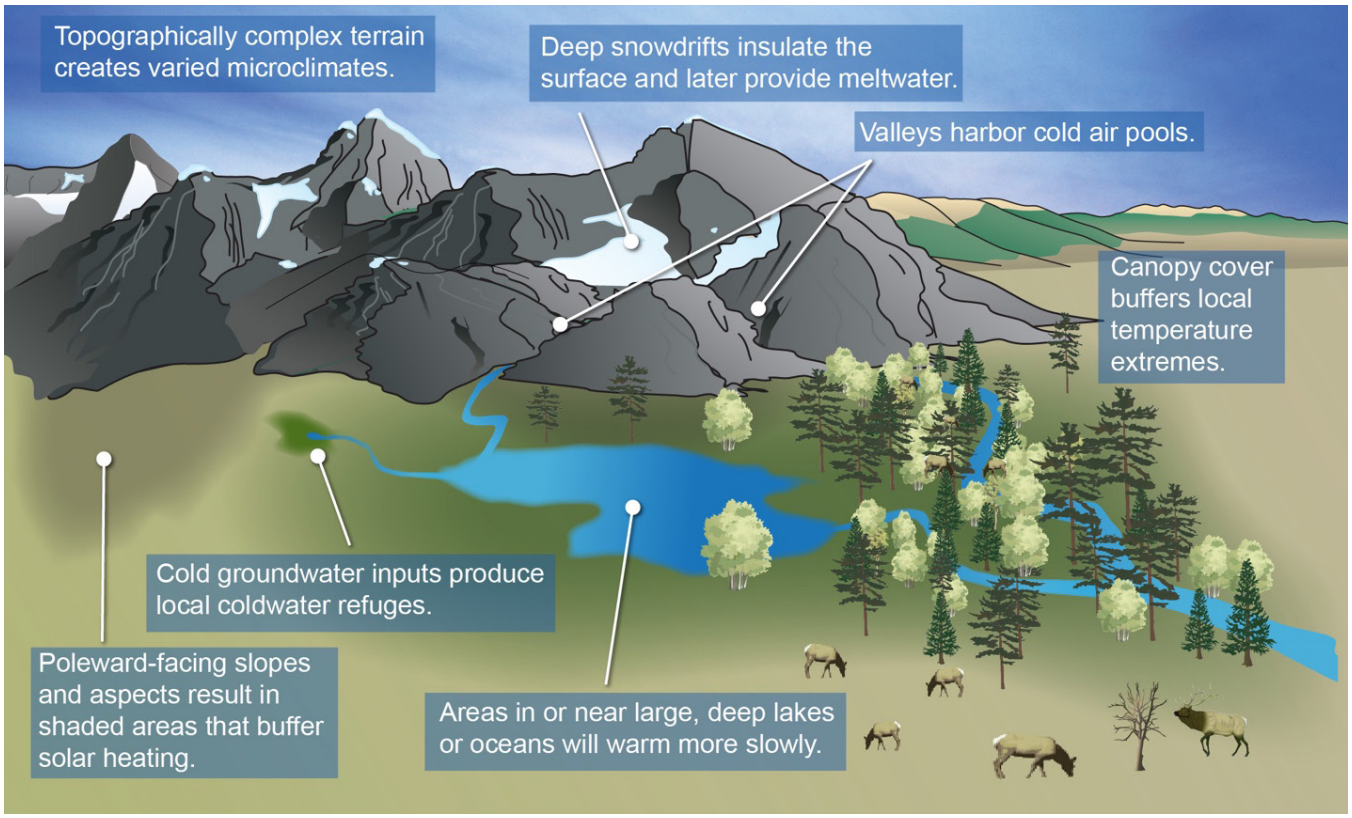


Climate change is leading to shifts in phenology and range for species across the United States.

Figure 8.11. Many plant and animal species are shifting to higher elevations, to more northern latitudes, or in multiple directions (here labeled "regional advancement"). The timing of seasonal activity is similarly shifting in response to warmer temperatures and changing precipitation regimes, in many cases occurring earlier in the year, although the direction and magnitude of changes are species-specific. Figure credit: University of Arizona and USFWS.

Conditions can change over very localized scales, creating complex "mosaic" patterns of environmental stressors.[117,118,119,120] Climate refugia occur in locations where environmental conditions are changing more slowly than in surrounding areas[121] or where local drivers override more regional-scale processes.[122] These refugia are expected to support organisms that can repopulate other depleted areas through dispersal via currents or land corridors[123] and are therefore a priority for conservation (Figure 8.12).[124,125] Identification of the many existing refugia expected to disappear under climate change is crucial.[126,127]

Environmental Mosaics and Climate Refugia



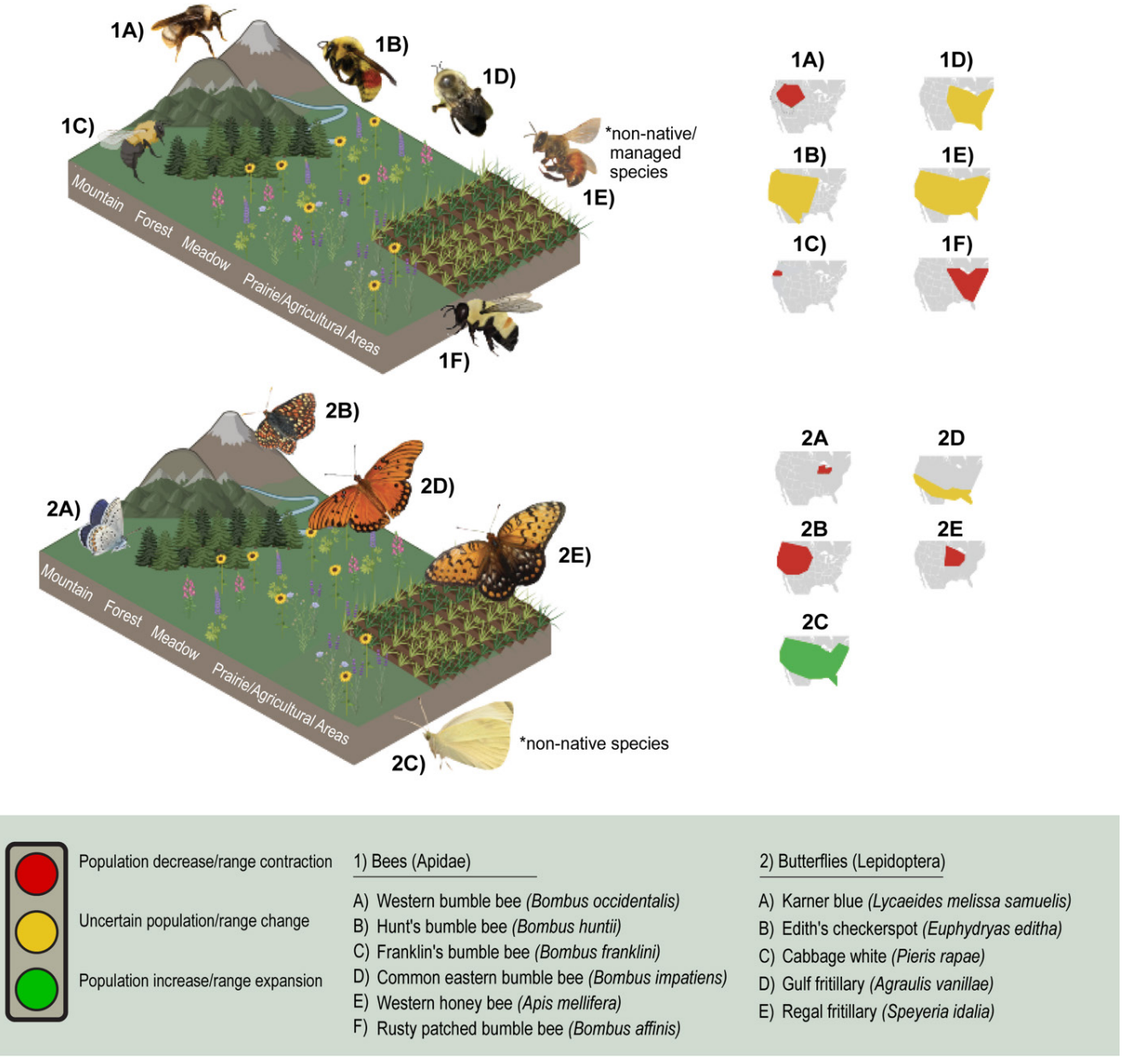
Climate refugia are locations where environmental conditions are changing more slowly than in the surrounding region.

Figure 8.12. Refugia help populations survive extreme events, and when connected via dispersal currents and corridors can serve as rescue sites.[122] Understanding variations in environmental exposures and organism sensitivities to extreme conditions helps forecast climate impacts[122,127] and inform management strategies.[128,129] Adapted from Morelli et al. 2016[130] [CC0 1.0].

Species Sensitivities and Extinction Risks

Understanding species sensitivities to climate impacts and adaptive capacity can help detect ecological tipping points (KM 8.1).[131,132] Large-bodied animals (Box 8.1)[133] and species occupying polar habitats are particularly at risk of local extinction due to physiological vulnerabilities.[134] In contrast, smaller-bodied species often have more widely variable responses to changing conditions (Figure 8.13).

Observed Pollinator Sensitivities



Insect pollinator responses to environmental stressors, even within the same taxonomic grouping, can vary widely.

Figure 8.13. Pollinator responses to changing climate conditions within a short time frame (the past 10–30 years) are leading to complex patterns of species movements across the landscape. Several species of bumble bees (**panel 1**) have had different responses over the past 10 years, from shifting in habitat within their ranges to range contractions and extinction risks. In **panel 2**, butterfly species are responding with declines and shifts within existing ranges or with range expansions nationwide. Figure credit: Colorado State University.

Box 8.1. Case Study: Climate Sensitivities of North Atlantic Right Whales

The North Atlantic right whale (*Eubalaena glacialis*) is one of the world's most endangered large whales, primarily due to historical commercial hunting, with fewer than 350 individuals remaining.[135] This species is vulnerable to climate change–driven extinction in part because of its large size, long lifespan, slow growth, delayed maturity, and small number of offspring.[136] Population recovery has been hindered by climate-driven changes in the distribution, availability, and quality of zooplankton, which has altered whale foraging patterns (KM 10.1).[133,137,138] As finding shelter and food becomes more difficult, the whales become more susceptible to disease, fishing gear entanglements, and vessel strikes, contributing to decreased body size and reproductive success (Figure 8.14).[139,140] Loss of these whales can have cascading effects on ecosystem composition and function.[141]

Threats to North Atlantic Right Whales



Climate change increases risks to the endangered North Atlantic right whale.

Figure 8.14. The whale known as Snow Cone is shown with her newborn calf near Cumberland Island, Georgia, in 2021. She was entangled in fishing rope for at least two years and is currently presumed deceased. Such threats are exacerbated as whales travel into new feeding areas because of changing oceanographic conditions. Photo credit: ©Georgia Department of Natural Resources/NOAA Permit #20556.

Disease Risks

Disease threats to wildlife, plants, and humans have emerged as a significant climate change risk.[142,143,144,145,146,147] Climate change promotes range expansions and population growth of disease-spreading (vector) species, increased host susceptibility via stress, and enhanced pathogen transmission (Table 8.1; KM 15.1),[148] with major economic consequences.[149,150] Diseases often thrive where other stressors are present; prevalence is projected to further increase as populations and ecosystems become stressed from temperature variation and extreme events, changes in habitats, altered migration patterns and ranges, biodiversity loss, and increases in invasive species (KMs 15.1, 30.4; Figure A4.16).[151,152,153,154]

Table 8.1. Climate-Impacted Disease Risks in Humans and Wildlife

Numerous wildlife and human diseases (KM 15.1) are expanding to new areas and species and becoming more common as climate change expands vector ranges and changes species interactions and habitat preferences. Sources: Islam et al. 2022; Gilbert 2021; Ogden et al. 2021; Sonenshine 2018; Keesing and Ostfeld 2021.[152,153,155,156,157]

Pathogen: Virus

Disease	Affected Organisms
West Nile virus	Birds and mammals
Viral hemorrhagic septicemia virus	Freshwater and marine fish
White spot syndrome virus	Aquatic crustaceans
Tomato spotted wilt virus	Plants

Example of impacts: Viral hemorrhagic septicemia damages wild and farm-raised fish such as rainbow trout, with patterns of spread and establishment being highly correlated with climatic variables (temperature, precipitation).[158]

Pathogen: Bacteria

Disease	Affected Organisms
Furunculosis	Trout and salmon
Enteric red mouth disease	Freshwater and marine fish
Citrus greening	Plants

Example of impacts: Citrus greening is a bacterial disease transmitted by an invasive insect (Asian citrus psyllid). Because the disease is highly sensitive to temperature, climate change is expected to allow it to spread farther.[159] Since 2005, Florida citrus production has declined 74%.[160]

Pathogen: Fungus

Disease	Affected Organisms
White-nose syndrome	Bats
Chytridiomycosis	Amphibians
Rapid ʻŌhiʻa death	Plants
Armillaria root rot	Plants

Example of impacts: Rapid ʻŌhiʻa death is a fungal disease that impacts ʻŌhiʻa lehua, a Hawaiian keystone species with important functional and cultural roles. Large-scale mortality is projected to worsen in a warmer and wetter climate.[161]

Pathogen: Parasite

Disease	Affected Organisms
Avian malaria	Birds
Proliferative kidney disease	Salmon
Brainworm	Moose, elk, caribou
Seagrass wasting disease	Aquatic plants

Example of impacts: Brainworm is a parasitic nematode spread via white-tailed deer, which are currently expanding farther northward. In moose, population declines due to brainworm are already affecting subsistence hunting among some Tribal communities.[162]

Pathogen: Unknown

Disease	Affected Organisms
Stony coral tissue loss disease	Corals
White band disease	Corals
Colony collapse disorder	Bees

Example of impacts: Stony coral tissue loss disease originated in Florida in 2014 and has spread throughout the Caribbean, with thermal stress implicated in reef vulnerability. The disease affects more than 30 coral species, including many important reef-builders. Rapid spread and high mortality rates have had serious economic consequences for tourism and fishing.[163]

Invasive Species Risks

Climate change has created uncertainty about where and how fast invasive species will spread, but there are both observed cases[164] and projections showing expected increases.[165] For example, cold-sensitive invasive species such as the kudzu vine (*Pueraria montana* var. *lobata*) can spread northward with warming.[166] Some invasive species are more successful than natives—particularly certain terrestrial plants[167] and aquatic species[168]—because they better tolerate or more rapidly adapt to changing conditions (Figure 8.15). Yet not all invasive species are favored by climate change; many invasive plants and vertebrates may experience decreased ranges while the ranges of many invasive invertebrates and pathogens are expected to increase.[169]

Invasive Species and Climate Change



Damaging invasive species that are expected to shift in range because of climate change.

Figure 8.15. Examples of invasive species include the following: (**a**) Hemlock woolly adelgid, an insect pest, is expected to spread northward with warmer winters and cause die-offs of eastern hemlock trees.[170] (**b**) Invasive carp are expected to benefit from warmer waters and expand into the Great Lakes, where they will compete with native fishes and present boating hazards through their habit of jumping out of the water.[171] (**c**) Eurasian watermilfoil chokes freshwater systems and outcompetes natives in warmer conditions.[172] (**d**) European green crabs, which benefit from warmer waters, harm economically important native shellfish fisheries.[173] Photo credits: (a) Kerry Wixted via Flickr [CC BY-NC 2.0]; (b) Steve Hillebrand, USFWS; (c) ©Stephen K. Hamilton, Cary Institute of Ecosystem Studies; (d) ©P. Sean McDonald, University of Washington.

Assisting Species Adaptation

Natural resource managers are implementing adaptation actions including increasing conservation efforts, reducing habitat fragmentation, protecting wildlife corridors, assisting species migration, and expanding protection activities.[174] For example, marine protected areas can reduce non-climate stressors like overfishing and facilitate recovery of populations following extreme events like heatwaves, which then benefits recreational and commercial fishing in surrounding areas (KM 28.2).[175] Many states now include climate impacts in state wildlife action plans; for example, Massachusetts has identified habitat patches allowing for movement of the threatened Blanding's turtle and is creating habitats that balance increased drought and other threats.[176,177,178]

Managing for connectivity can enhance species climate resilience, particularly for wide-ranging and migratory species.[179] Priorities include connecting climate refugia, areas of high diversity,[123,180] and current and future habitat types.[181] For example, resilience strategies for the saltmarsh sparrow (*Ammospiza caudacuta*), which has declined dramatically due to rising sea levels, include protection of areas expected to convert into future wetlands, use of runnels and other elevation manipulations, and high-marsh restoration.[182,183]

Assisted migration has been implemented for at-risk species such as the Laysan albatross, Oʻahu tree snail, relict leopard frog, and wolf (Figure 8.16).[184] In the Chippewa National Forest in Minnesota, seeds of tree species native to red pine forests but collected 100–200 km to the south—and thus genetically distinct from local populations—are being planted to test assisted migration.[185]

Managing for Species Adaptation



Assisted migration can help species adapt to changing climate conditions.

Figure 8.16. One example is the translocation of wolves to Isle Royale National Park, Michigan. The loss of ice bridges in winter prevented new arrivals that would have maintained genetic viability of the population.[186] Photo credit: Jacob W. Frank, NPS.

Implications for Management

While protected areas can help species adapt to climate change, these areas are themselves vulnerable;[174,187,188,189] many US protected areas are expected to see major shifts in vegetation communities and other species.[190] Further, the existing US protected areas system has low overlap with projected climate refugia;[191] extending protection to include future habitat suitability for some species may double costs.[192] Given continued range shifts, areas with priority species that draw tourists (e.g., bird watchers) will need to refocus as some species become rarer or disappear,[193,194] impacting neighboring communities dependent on tourism revenue.

Conflicts (between humans and with wildlife) arising from climate-driven changes in distribution and availability of species and resources are occurring.[195,196] For example, some species are moving out of areas set up to conserve them, and range shifts of fish stocks (including across international boundaries) are causing challenges (KM 10.1).[197,198] Some adaptation policies (e.g., translocation of nonhuman species into human communities unwilling to coexist with them) may exacerbate conflicts (KM 17.2).[199] Adaptive management that prioritizes both climate change response planning and conflict management can reduce negative outcomes.[195,200,201]

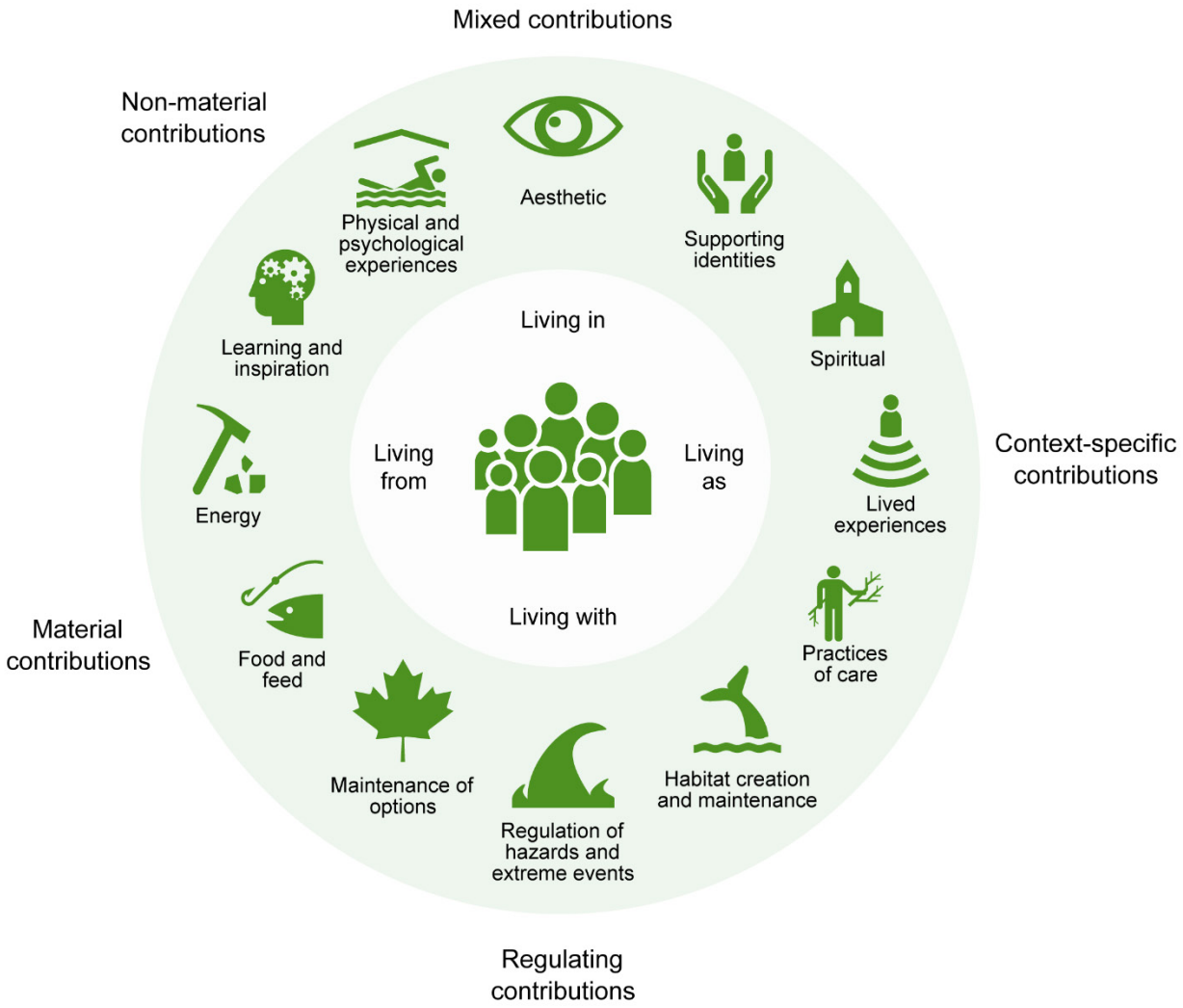
Key Message 8.3

Impacts to Ecosystem Services Create Risks and Opportunities

Climate change is having variable and increasing impacts on ecosystem services and benefits, from food production to clean water to carbon sequestration, with consequences for human well-being (*very likely*, *high confidence*). Changes in availability and quality of ecosystem services, combined with existing social inequities, have disproportionate impacts on certain communities (*very likely*, *high confidence*). Equity-driven nature-based solutions, designed to protect, manage, and restore ecosystems for human well-being, can provide climate adaptation and mitigation benefits (*likely*, *medium confidence*).

Ecosystem services provide substantial and often economically important contributions to communities, ranging from direct material benefits like food production and clean water to nonmaterial benefits like recreation (Figure 8.17). However, economic valuation alone does not reflect intrinsic or relational values that people hold toward nature;[202,203] for example, Tribal and Indigenous Peoples rely on ecosystems for supplies of culturally valuable food, materials for religious ceremonies, and relational links within communities and among generations (KM 16.1).[204,205]

Ecosystem Services and Their Benefits



Ecosystems provide a broad range of relational benefits, from the material to the spiritual.

Figure 8.17. Ecosystem services, also called "nature's contributions to people," are the benefits that humans receive or derive from ecosystems. These are both material (e.g., energy sources) and non-material (e.g., sense of place), and contribute to the regulation of ecosystem processes. The broad categories of benefits pictured are fluid and overlapping. People value nature in multiple ways, such as "living as" nature (e.g., Indigenous viewpoints that humans are part of the environment; Figure 16.3) or "living from" nature (e.g., people's dependency on key services). Adapted from O'Connor and Kenter 2019[206] [CC BY 4.0].

There are many adverse climate change effects on ecosystem services,[207,208] including reduced water availability for human and agricultural uses (KM 4.1), decreased productivity of crop species due to increased pest infestations (KM 11.1), and losses of hazard-mitigating ecosystems like wetlands and coastal shorelines that provide nursery and nesting habitat, recreation, and aesthetic pleasure (Table 8.2; KM 9.2). However, future trends on ecosystem use and benefits are not always clear. For example, rising temperatures can extend seasonal recreational opportunities, but if daily high temperatures exceed 27°–30°C (80.6°–86°F), recreation tends to decrease.[209,210]

Further, diminished benefits from ecosystem services can also occur based on other factors.[211,212] For example, discriminatory planning practices, housing segregation, and racism have created inequitable distributions of services, leading to communities of color experiencing reduced access to benefits like improved air quality or heat reduction (KM 12.2; Figure 12.6).[213,214,215] Lack of access often accompanies other environmental harms (e.g., greater exposure to allergens or risks of green gentrification, the displacement of local residents as environmental benefits improve).[216,217] Climate change is expected to exacerbate these impacts[207] and create further difficulties in addressing environmental racism, highlighting the need for clear management priorities and recognition of diverse values.[218,219]

Table 8.2. Examples of Climate Impacts on Ecosystem Services

Climate change affects the availability and quality of many ecosystem services, and many projected impacts on important ecosystem services will also have equity implications.

Ecosystem Service	Potential Climate Impacts	Equity Implications
 **Regulation of Natural Hazards**	Coastal marsh retreat is projected due to sea level rise and increased storm activity.[220]	Flood risks are often inequitably distributed; for example, property damage risks can be disproportionately higher for Black communities.[221]
 **Physical and Psychological Experiences**	Cold-weather recreational opportunities are projected to decline (e.g., fewer skiing days).[209,210,222]	Less green space access in low-income communities and communities of color already results in fewer opportunities for recreation.[223,224]
 **Water Quantity**	Changes in precipitation, snowpack, soil moisture, and evapotranspiration are projected to alter surface and groundwater availability (KM 4.1; Figure A4.7).	Drought often has disparate impacts;[225] for example, Tribal reservations in the US Southwest with higher agricultural dependence will be particularly impacted.[226]
 **Regulation of Air Quality**	Street trees provide considerable urban air quality benefits but are vulnerable to drought and heat.[227]	Existing tree canopy distribution is inequitable, accounting for greater air pollution[228,229,230] associated with legacies of redlining.[231]
 **Food Production (fisheries)**	Aquatic systems are experiencing shifts in species ranges, phenologies, distributions, and productivities.[232]	Culturally important species, such as Chinook salmon for Pacific Northwest Tribes, are projected to dramatically decline in the future.[233]

Opportunities for Nature-Based Solutions

Ecosystem-based mitigation and adaptation opportunities are often called nature-based solutions (NBSs) or natural climate solutions (Figure 8.18).[234,235] NBSs support biodiversity and can provide other benefits when managed in collaboration with affected communities and use of local knowledge (KM 21.1). For example, coastal wetland restoration provides both mitigation and adaptation benefits by sequestering carbon and decreasing coastal flooding, wave action, and erosion[236] while improving water quality and increasing habitat biodiversity (KM 9.3; Focus on Blue Carbon).[237] NBS projects are often very cost-effective, spurring new financing options.[238,239]

Ecosystem-based adaptation is a type of NBS aimed at increasing community resilience to climate change through the use of ecosystems.[240,241] Examples include protecting and restoring floodplains to help reduce flood impacts[242] or helping farmers cope with drought through soil conservation measures.[243] There are high returns on investments to restore coastal ecosystems in particular, since US coral reefs provide estimated adaptation benefits of more than $1.8 billion annually (dollar year not provided).[244,245] These approaches can also have positive equity benefits when designed with local participation and buy-in through collaborative approaches (KM 31.4).[246,247,248,249,250,251]

Nature-Based Solutions

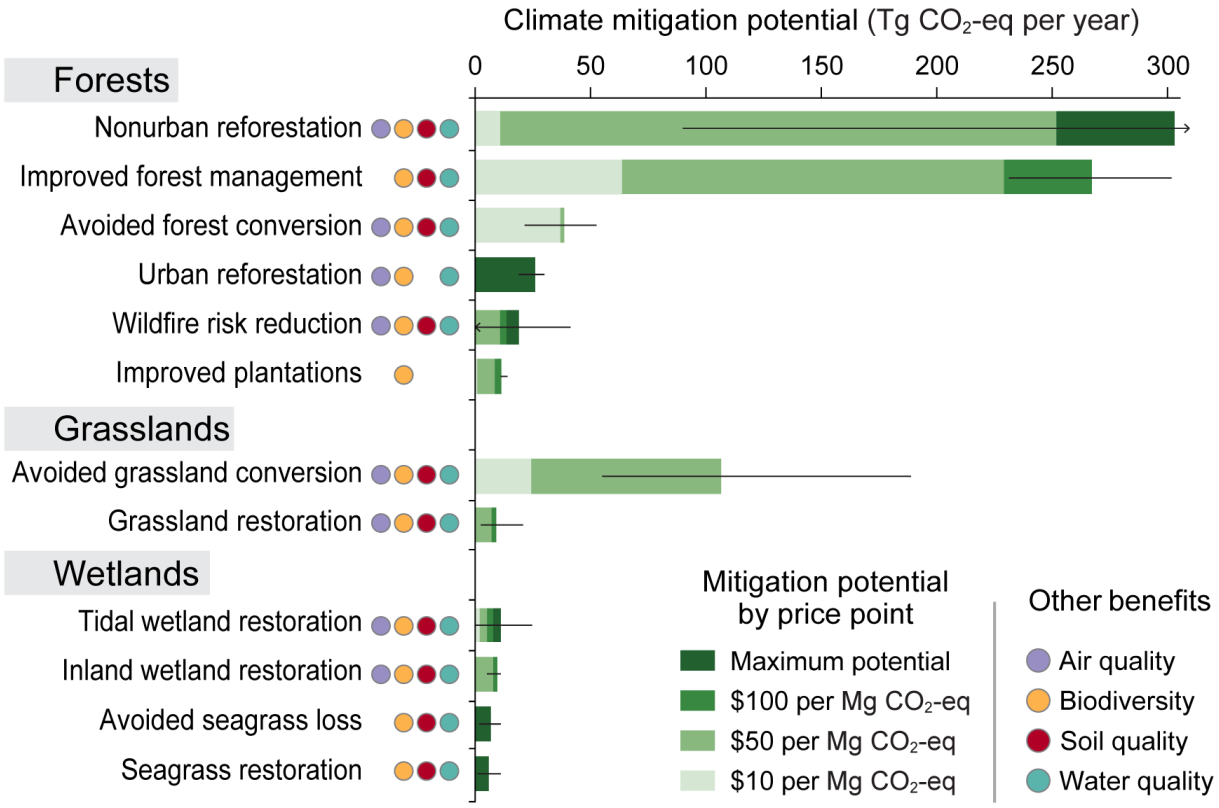


Nature-based solutions buffer the effects of climate change.

Figure 8.18. Nature-based solutions (NBS) are actions to protect, manage, and restore ecosystems to address societal challenges such as climate change. Examples in the US include (**a**) oyster restoration; (**b**) cover cropping; (**c**) stormwater management; and (**d**) urban agriculture. These not only help buffer the impacts of climate change, such as through physical barriers or improved local microclimates, but also provide additional benefits like food and habitat provisioning.[252,253,254] Figure credit: Rutgers University and NPS. See figure metadata for additional contributors. Photo credits: (a) Linda Walters, NPS; (b) David Bosch, USDA; (c) Alisha Goldstein, EPA; (d) Bob Nichols, USDA.

Current and future opportunities for NBSs exist across the US, particularly for mitigation solutions focused on protecting and increasing carbon storage by natural ecosystems (Figures 6.6, 8.19; Focus on Blue Carbon).[255] Planning for future protected areas for both climate and biodiversity could emphasize areas that not only hold large amounts of carbon but also help species adapt,[256] recognizing the important role that many animal species play in carbon cycling.[257] However, NBSs themselves are also vulnerable to rising temperatures, sea level rise, and other climate impacts.[258]

Climate Mitigation Potential of Nature-Based Solutions in 2025



Nature-based solutions can support carbon storage while also providing other benefits.

Figure 8.19. Nature-based solutions (NBSs) can preserve or enhance carbon storage in soils and biomass across natural systems like forests, grasslands, and wetlands, as well as agricultural lands. Different approaches vary in their climate mitigation potential, shown here as teragrams of carbon dioxide equivalent (Tg CO_2-eq per year; length of bars) in the year 2025. Lighter green shades indicate the estimated portion of mitigation obtainable for less than $10, $50, or $100 per megagram of CO_2-eq (Mg CO_2-eq). The dark green "Maximum" category shows the highest technical carbon sequestration potential that is also consistent with meeting human needs for food and fiber. Black lines are error bars indicating either the 95% confidence interval or an uncertainty range, depending on the source of the estimate. The arrow indicates a range that may exceed the values shown on the chart. Other potential benefits of NBSs are also indicated for each category (colored dots). Figure addresses contiguous US only. Adapted from Fargione et al. 2018[259] [CC BY 4.0].

NBSs that involve restoring degraded ecosystems can improve resilience[260] and increase provision of ecosystem services.[261] Ideally, restoration is designed to recover a range of potential benefits.[262,263] However, multiple services cannot necessarily be maximized simultaneously, as focusing on one ecosystem service at the expense of other benefits leads to trade-offs.[264,265,266] Larger-scale restoration efforts are generally more successful when connected to local priorities,[267] including their use in addressing environmental inequities (Box 8.2).[268]

Box 8.2. Restoration and Ecosystem Management by Tribal Nations

Tribal forestry programs throughout the US provide exemplary models of Indigenous land management practices that showcase Tribes' ability to balance sustainable environmental stewardship, fulfilling the social, ecological and economic needs of their communities.[269] The "anchor forests" concept, in which Tribes are at the center of multiple landownerships and serve as the primary hub for providing forest management infrastructure, is one effective approach. Such initiatives maximize concepts of Tribal sovereignty and Indigenous Knowledge to restore forests at the pace and scale needed to mitigate and adapt to rapid climate change.[270] Furthermore, traditional and contemporary Indigenous management practices that support both cultural and spiritual relationships with nature and an equitable climate transition can serve as critical pathways to sustaining ecosystems (KMs 7.3, 16.1).[271] Incorporating local knowledge and Indigenous Peoples in the co-development of restoration activities can produce considerable benefits.[272]

Traceable Accounts

Process Description

The chapter lead author, coordinating lead author, and agency chapter lead authors discussed the Fourth National Climate Assessment (NCA4) ecosystems chapter and brainstormed topics that had emerged since then or were not well covered. The chapter lead author also pulled out key gaps identified from the US Global Change Research Program assessment review document and public comments. A tentative list was compiled of authors with expertise in ecosystems, biodiversity, and ecosystem services; marine, freshwater, and terrestrial systems covering NCA regions; and ecosystem types. The final author team comprised a mix of federal agency scientists and academic experts with varying experience in assessments and past NCAs. Key Messages were developed by the full author team through virtual meetings from fall 2021 through spring 2022, with additional inputs from a public engagement workshop held in January 2022, in which over 100 people participated virtually to suggest topics for review by the chapter. A Youth Dialogues public engagement workshop was held online in February 2022 in partnership with the Youth Environmental Alliance in Higher Education and Rutgers Climate Institute. Federal agency reviews in summer 2022 provided further suggestions for improvement, as did additional public comments and the National Academies review in spring 2023. At the April 2023 in-person meeting in Washington, DC, the author team collectively discussed the wording and confidence levels for the three Key Messages to ensure consensus around the statements.

Since NCA4, a plethora of research has been published describing how ecosystems are changing or are expected to change further in the face of climate change and other stressors, along with numerous specific species and ecosystem services impacts. The evidence base for this report is therefore heavily weighted to peer-reviewed journal articles published in the last five years.

Key Message 8.1

Climate Change Is Driving Rapid Ecosystem Transformations

Description of Evidence Base

Ecosystem Regime Shifts

Many examples of regime shifts resulting from transformative changes are already documented, and the evidence base is strong across multiple ecosystem types,[273] including forest transformations to grassland or woodland following increased wildfires; widespread die-off of pinyon pines from drought and bark beetle infestations; and shifts from healthy kelp forests to urchin barrens due to epizootic disease and marine heatwaves in nearshore marine environments.[144,274,275,276,277,278,279,280] Overall, regime shifts of temperate ecosystems toward more subtropical ones at their southern limits are expected in response to future decreases in the frequency and intensity of extreme cold events.[45] For example, mangrove forests in Florida and along the Gulf Coast are projected to expand northward into present-day salt marshes.[43]

Monitoring

Systematic biodiversity surveys, digitized museum records, and long-term automated data collection have all demonstrated the importance of multiple methods of monitoring of environmental changes through strong evidence bases.[281,282,283,284]

Major Uncertainties and Research Gaps

Complexity of Impacts on Ecosystems

The ability to predict ecological responses to changing climate conditions remains a key gap for most ecosystems because of complex interactions among species, the potential for adaptation (through both evolutionary responses and human activity), and the intersection of climate change with other drivers of change.[36,285,286] For example, warmer temperatures can lead not only to increased forest regeneration and tree growth but also to increased mortality of older trees through wildfires, insects, and disease, with the resulting net impacts highly uncertain.[287] Warmer winters are generally expected to benefit forest pests,[288] but complex interactions among pests, their hosts, and other disturbances can make the combined effects more muted than otherwise expected.[289,290,291] Recent research suggests that multiple disturbances can have counteracting effects, although patterns are not always clear, and sometimes intensified combined effects (synergies) also occur.[292,293]

Monitoring

There are a number of gaps in comprehensive, long-term ecological monitoring to detect changes and to predict the risks of future climate change.[48] Improved knowledge of biological response mechanisms that drive ecological changes[36] will enable better anticipation of ecosystem shifts, especially for systems dominated by long-lived species and where impacts emerge after a time lag;[294,295] this makes eliminating monitoring gaps (e.g., in Arctic and ocean regions) critical. Community monitoring programs are promising but can be biased (e.g., lack of uniform sampling) toward particular regions or species.[296]

Adaptive Management

While adaptive management is widely considered an effective approach for managing uncertainty through learning in order to conserve, manage, and restore ecosystems and species populations,[297] successful implementation is limited by the lack of effective monitoring mechanisms,[298] challenges in dealing with uncertainty, and lack of appropriate institutional mechanisms for its implementation, among other problems.[299,300,301,302] As a result, an adaptive governance approach is increasingly understood as a broader and more promising mechanism for addressing the social and institutional requirements of adaptive management while also facilitating social–ecological transformation.[300,303] However, the adaptive governance approach also has its own conceptual and implementation challenges that need to be addressed in order to enhance success, given insufficient evidence on effective implementation[298] and questions about its capacity to bring about transformational changes.[304] There is also potential for undesirable outcomes, such as inadequate consideration of power and social equity issues.[305,306,307,308] Moreover, there are gaps in research on enhancing the transition process toward adaptive management and governance and associated outcomes,[309] as well as lack of clarity on the synergies and trade-offs among determinants of the capacity for adaptation and transformation.[310,311]

Description of Confidence and Likelihood

A growing body of empirical field studies and monitoring programs shows that climate change, in concert with other stressors, is driving transformational changes across many ecosystems and that changes will accelerate with continued warming (*very likely*, *high confidence*). Given the growing impacts of ecosystem change, the serious implications for human well-being were also considered *very likely*, and the authors assessed *high confidence*, given the empirical studies across multiple ecosystems (i.e., not just projections)

showing that a range of well-being impacts are already being experienced across economic, cultural, and social systems. As Chapter 2 has indicated, extreme events are increasing in frequency and/or severity, and these events are more frequently implicated in abrupt ecosystem changes; but because of limited studies examining the direct correlation of extreme events on abrupt ecosystem transformations, the authors assessed only *medium confidence*. The authors also note that adaptive governance frameworks, adaptive management, and monitoring all play a role in helping to cope with climate changes; but given the paucity of evidence of long-term impacts of adaptive governance, the authors assessed only *medium confidence*.

Key Message 8.2

Species Changes and Biodiversity Loss Are Accelerating

Description of Evidence Base

Range Shifts

Shifts in species ranges in response to changing climate occur across a wide range of species and are expected to accelerate.[312,313] The evidence base is strong across a wide range of marine, plant, invertebrate, reptile, bird, and mammal species; selected examples are shown in Figure 8.11, but many more exist. Further, there is strong evidence for the patterns of range shifts differing among types of species; for example, multiple studies have shown that marine species have expanded their ranges more readily than terrestrial species, with shifts in distributions occurring more quickly as well,[314,315] whereas terrestrial species tend to have greater behavioral adaptations and less physiological sensitivity to temperature changes.[316,317,318]

Phenological Changes

The evidence base of documented responses in the timing of life cycles to climate change is strong, ranging from earlier flowering dates in many parts of the country, to shifts in hibernation of mammals, to timing of egg laying of frogs.[319,320] Very rapid changes can be easily observed, for example, in short-lived plants that have high turnover rates and more rapid genetic adaptation,[321] lending strength to the evidence base.

Extinction Risks

Long-term studies (i.e., decades) are needed to discern the fingerprints of climate change on long-lived animals,[322] which can be challenging. But some impacts are in evidence; for example, sea level rise is expected to impact nesting site availability and quality for sea turtles, while warming temperatures can affect sex ratio of offspring.[323,324] Refugia have potential to mitigate some extinction risks for species able to take advantage of them, but the evidence base is fairly new. Further, emerging modeling studies have indicated that these areas, too, are at risk; for example, Ebersole et al. (2020)[127] found that under a 4°C (7.2°F) warming scenario, there was a >50% probability that refugia for freshwater fish species would decrease in area by 42%–77% by 2070.

Disease Risks

Disease risks are occurring as a result of many factors and across different hosts and pathogens; given the large number of potential risks, meta-analyses have been helpful in providing overviews of the evidence base. One comprehensive review of infectious diseases spread between humans and animals found that 58% of diseases worldwide have been exacerbated by climate change (e.g., warming, altered precipitation, and floods).[154] Only 16% of diseases were diminished by climate change. A global analysis of thousands of wildlife populations indicated that climate warming exacerbates wildlife disease throughout the temperate zone worldwide and is expected to increase wildlife disease in the United States.[325] A different global analysis of 6,801 ecological assemblages demonstrated that human-dominated ecosystems strongly favored animal

species that host human disease pathogens while decreasing the presence of non-host animals,[326] a strong evidence base for the finding that stressed ecosystems tend to experience more disease risk.[153] Many empirical examples of ongoing disease outbreaks—e.g., fish kills and large-scale coral disease outbreaks following coral bleaching events—have increased in number and are evidence of perturbed aquatic systems where disease stresses are exacerbated by warming.[144,146] The well-documented catastrophic declines in amphibian populations caused by the invasive chytrid fungus *Batrachochytrium dendrobatidis* have also been well linked to warming conditions.[327]

Major Uncertainties and Research Gaps

Range Shifts

The speed and extent of some species range shifts remain uncertain. Climate envelope models use current relationships among species ranges and climatic characteristics to project how ranges may shift in the face of climate change,[328] yet they necessarily assume that climate is the main constraint on ranges and that species rapidly respond. In reality, species responses can be slowed and limited by dispersal ability, natural and human-created barriers, and species interactions.[329,330]

Moreover, climate change is expected to present organisms with novel environmental conditions, making predictions based on historical relationships problematic.[331] Specifically, improving such predictions would require a better understanding of the degree to which range shifts occur due to longer-term climatic changes versus periodic extreme weather events such as heatwaves brought on by those climatic changes.[86]

While climate refugia are increasingly discussed in the literature, they are themselves vulnerable to climate impacts, and there is uncertainty about their persistence and resilience.[126,127]

Phenological Changes

The individual and variable responses of species to climate change is expected to disrupt important biological interactions. Many risks posed by emerging mismatches among interacting species remain unclear,[332] as do needed management responses to reduce economic and social impacts.

Diseases and Invasives

Impacts of climate change on species health are complex and difficult to generalize across systems;[291] for example, the role of climate change among other drivers of the spread of tick-borne diseases, like changes in land use or human behavior, remains a topic of some debate.[152,156]

Studies showing that invasives could be limited in response to climate change are based mostly on studies of terrestrial species whose range shifts are often limited by oceans,[169] indicating that more research is needed on different types of species to improve projections.

Description of Confidence and Likelihood

There is *high confidence* that the interaction of climate change with other stressors will *very likely* lead to biodiversity loss, changes in species distribution and life cycles, and increasing impacts from invasives and diseases, given a very well-documented range of species changes across multiple ecosystem types, as well as clear economic and social consequences in many regions already experiencing these impacts. The evidence is strong, and the authors assessed *high confidence* that some species, particularly those that cannot easily relocate and those that are highly temperature sensitive, are facing heightened extinction risks, and that these are *very likely*, given that some species populations are already in serious decline at current levels of warming. Policy actions to help species adapt were assessed, and what they have in common is a clear identification of risks and prioritization of species and locations for protection. The

evidence base for these policy actions is clear, and the authors have *high confidence* that such actions can expand and improve options for management.

Key Message 8.3

Impacts to Ecosystem Services Create Risks and Opportunities

Description of Evidence Base

Access to Ecosystem Services

There is strong evidence that communities of color experience greater air pollution inequity[228,229,230,231] compared to White communities and have reduced and/or less high-quality access to green space, trees, and other ecosystems that buffer these impacts. Limited access to resources and services also extends to those with limited income or wealth (also known as economic capacity), and these factors interact with race and other social hierarchies, including power, in complex ways.[333]

Climate Impacts on Ecosystem Services

There is strong evidence at the global level that warming and carbon dioxide fertilization effects have already altered some ecosystem services, such as coastal carbon storage and ecosystem biodiversity, as noted in the recent Intergovernmental Panel on Climate Change report.[2] For the US, while not all ecosystem services have been quantitatively assessed for climate impacts, those that have been show either currently observable declines (e.g., nearly 40% of pollinator-dependent crops in the US suffer from low pollinator abundance)[334] or projections of future decline (e.g., reduced outdoor recreation opportunities by 2050).[210]

Restoration

Evidence for the effectiveness of restoration at improving ecosystem service benefits is growing as more landscape-scale restoration is undertaken across multiple ecosystems.[263] Additionally, valuation of ecosystem services benefits has proven to be a strong driver of new restoration programs, as it helps identify potential ecosystems to manage or restore (e.g., how health benefits can be obtained from restoration of vegetated terrestrial systems).[262]

Major Uncertainties and Research Gaps

Measurement, Valuation, and Management of Ecosystem Services

There remain challenges in measuring, monitoring, and evaluating the impacts and effectiveness of many ecosystem services.[335] In the US, urban spaces continue to be under-researched, especially in communities of color, despite often being biodiverse environments;[336] and current research is usually limited to city-specific case studies of ecosystem services measurements and analyses, with less focus on comparative work.[248,337] Furthermore, many city planning documents do not include climate change adaptation practices regarding cultural services or environmental injustice in ways that translate to implementation[338] and instead focus on physical and natural resources, costs, or logistics.[247] Research that engages communities, residents, and small organizations in identifying and designing measurements, valuation, and management criteria is a persistent gap, given the continuing lack of resident participatory research and community science in identifying problems and implementing solutions. A few studies have connected multiple types of urban ecosystem services from a theoretical planning point of view,[248,337,339] but integrating justice into ecosystem service practices by prioritizing community needs, aligning methods of assessment and criteria to goals, and addressing environmental racism is a critical gap.[247]

Restoration

There are few examples of ecological restoration practices designed to be resilient to climate change,[340,341] with particular challenges around making decisions about what needs to be "restored"[342] and to what conditions or baseline, as well as how to minimize vulnerability to extreme climate events that may be unprecedented in recent history. There can be spatial disconnects between where restoration actions need to be implemented and where ecosystem service improvements will be observed,[343] and the economic cost of restoration efforts and stakeholder preferences for desired states can prevent recovery efforts.[344]

Nature-Based Solutions (NBSs)

NBSs could cause risks of undesirable outcomes if they entail ecosystem transformations or species introductions over large areas of land; thus, they require careful study prior to implementation to avoid exacerbation of environmental and social injustices.[345,346] There are increasing cases of poorly designed NBSs and rising concern over second-order effects, like green gentrification.[216,217] However, there are considerable research gaps regarding how to avoid these outcomes. Evidence suggests that more stakeholder engagement in carbon removal projects and policies could help maximize adaptation benefits,[347] but this is an area of ongoing research.

Description of Confidence and Likelihood

There is *high confidence* that climate is having variable and growing impacts on many ecosystem services, based on an expanding literature containing many regional examples. These changes are assessed as *very likely*, given the existing levels of warming in areas where impacts have already been observed. There is *high confidence* that these changes in availability and quality of ecosystem services, when combined with existing social inequities that are also well documented, will result in disproportionate impacts on some communities. These disproportionate impacts were assessed as *very likely*, given that impacts are already visible, particularly in urban areas. The authors assessed it to be *likely* that nature-based solutions designed to be equitable can provide multifunctional benefits for climate adaptation and mitigation, although there is only *medium confidence* that current examples of nature-based solutions are able to fully address mitigation and adaptation needs in an equitable manner, given a growing body of evidence that poorly designed or inequitable nature-based solutions do continue to be implemented in some places.

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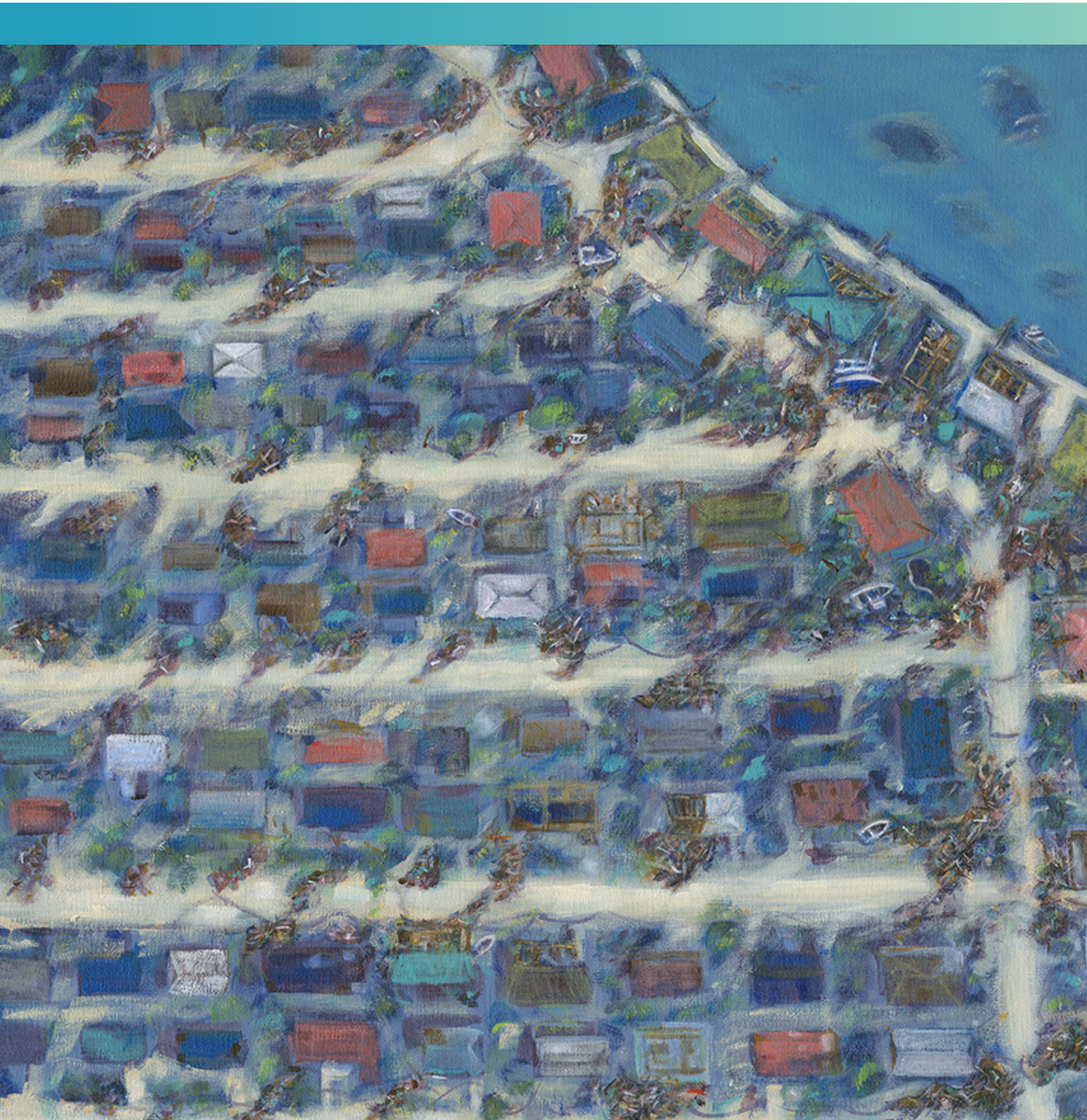
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Fifth National Climate Assessment: Chapter 9

Coastal Effects



Chapter 9. Coastal Effects

Authors and Contributors

Federal Coordinating Lead Author

Mark S. Osler, National Oceanic and Atmospheric Administration

Chapter Lead Author

Christine L. May, Pathways Climate Institute

Agency Chapter Lead Author

Hilary F. Stockdon, US Geological Survey

Chapter Authors

Patrick L. Barnard, US Geological Survey
John A. Callahan, NOAA Center for Operational Oceanographic Products and Services
Renee C. Collini, The Water Institute of the Gulf
Celso M. Ferreira, George Mason University
Juliette Finzi Hart, Pathways Climate Institute
Erika E. Lentz, US Geological Survey
Tucker B. Mahoney, Independent Coastal Engineer
William Sweet, NOAA National Ocean Service
Dan Walker, EA Engineering, Science, and Technology Inc.
Christopher P. Weaver, US Environmental Protection Agency, Office of Research and Development

Technical Contributors

Jamie Carter, NOAA National Ocean Service
Patrick S. O'Brien, US Army Corps of Engineers
Brittney W. Parker, NOAA National Ocean Service
Daisy R. Ramirez Lopez, Pathways Climate Institute

Review Editor

Hannah Baranes, Gulf of Maine Research Institute

Cover Art

Joan Hart

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Introduction

Our Nation's coasts support industries, commerce, communities, cultures, traditions, and recreation while also providing iconic landscapes and diverse ecosystem services. Observed sea level rise (SLR) and changes in the frequency and intensity of extreme storms, coupled with changes in land use and land cover that can magnify flood risk, have a significant and demonstrable negative impact on people living and working along the coast. Impacts are expected to worsen in the coming decades as SLR continues to accelerate. Observed and projected trends vary along our Nation's coasts (KM 9.1); therefore, consideration of local and regional trends is important when evaluating impacts (KM 9.2) and adaptation (KM 9.3).[1,2]

The number of people living in coastal areas at risk of SLR inundation (permanent inundation by daily high tides) or surge- or wave-driven flooding (temporary flooding driven by storm events) is in continual flux.[3] Between 1990 and 2020, the number of people living below high tide elevations plus 3.3 feet (1 m) of SLR increased by about 14%–18% to 2.2 million, consistent with continued growth and development.[3] Human modifications to coastal landscapes, such as seawalls and levees, can exacerbate flood risks and erosion[4,5,6] and affect the ability of coastal ecosystems to naturally adapt.[7]

Weather-related disasters continue to increase across US coasts (KMs 2.2, 3.5), with SLR amplifying the flooding and impacts to coastal communities. Between 2000 and 2021, 38 tropical cyclones caused over $1 trillion in losses (in 2022 dollars) and 6,200 deaths.[8] Federal, state, and local actions to reduce these losses are underway, yet progress is slow, and substantial wealth inequities, systemically sustained gaps in resources and capacity, and past injustices continue to disparately impact frontline communities, including Tribes and Indigenous Peoples, rural communities, and lower-income populations (KM 20.1). It is difficult to disentangle the vulnerabilities and consequences associated with climate change from histories and racial inequities that shaped social–environmental systems that exist today.[9] However, climate adaptation efforts that embed equity considerations, support environmental justice, and center the local communities may have the best chance of success, using adaptation strategies that range from protection-in-place to planned relocation.[10,11,12]

Increasing weather-related disasters and SLR also increase impacts on coastal ecosystems and natural shorelines, resulting in gradual (e.g., inland migration of wetlands) to abrupt (e.g., storm erosion of dunes and bluffs) changes that increase flood risks and damages to coastal communities and major infrastructure (e.g., highways, railroads, ports, airports, and other critical infrastructure; KM 12.2). The combined impacts will require fundamental reimagining of the coast. Protection structures can reduce risks on an interim basis; however, many communities and the infrastructure they depend on will need gradual relocation to higher ground, which can provide space for coastal ecosystems to adapt (KM 8.1). In some locations, coordinated and deliberate coastal relocation, implemented equitably, will be essential to reduce future risk to lives and livelihoods (KM 31.1).[13,14,15]

Key Message 9.1

Coastal Hazards Are Increasing Due to Accelerating Sea Level Rise and Changing Storm Patterns

The severity and risks of coastal hazards across the Nation are increasing (*very likely*, *high confidence*), driven by accelerating sea level rise and changing storm patterns, resulting in increased flooding, erosion, and rising groundwater tables. Over the next 30 years (2020–2050), coastal sea levels along the contiguous US coasts are expected to rise about 11 inches (28 cm), or as much as the observed rise over the last 100 years (*likely*, *high confidence*). In response, coastal flooding will occur 5–10 times more often by 2050 than 2020 in most locations, with damaging flooding occurring as often as disruptive "high tide flooding" does now if action is not taken (*very likely*, *high confidence*).

Accelerating Sea Level Rise

Global mean sea level is rising at an accelerated rate, with the average rate of about 0.05 ± 0.01 inches per year (1.2 ± 0.2 mm per year) over the pre-satellite era (1901–1990)[16] nearly tripling to 0.13 ± 0.02 inches per year (3.4 ± 0.4 mm per year) during the 30-year satellite era (1993–2022)[17] due to thermal expansion from warming waters and the growing contribution from melting glaciers and ice sheets.[18] Global SLR rates further accelerated to 0.17 inches per year (4.4 mm per year) over the last decade (2013–2022), although this acceleration may include components of natural variability due to the short time period.[19]

To help communities plan for an uncertain future, the US Interagency Sea Level Rise Task Force established five future SLR scenarios that span the range of plausible SLR amounts by 2100 using the latest scientific consensus from the Intergovernmental Panel on Climate Change (IPCC) and other scientific bodies.[2] The five SLR scenarios represent the range on a global scale, with projected SLR amounts in 2100 and scenarios defined as follows:

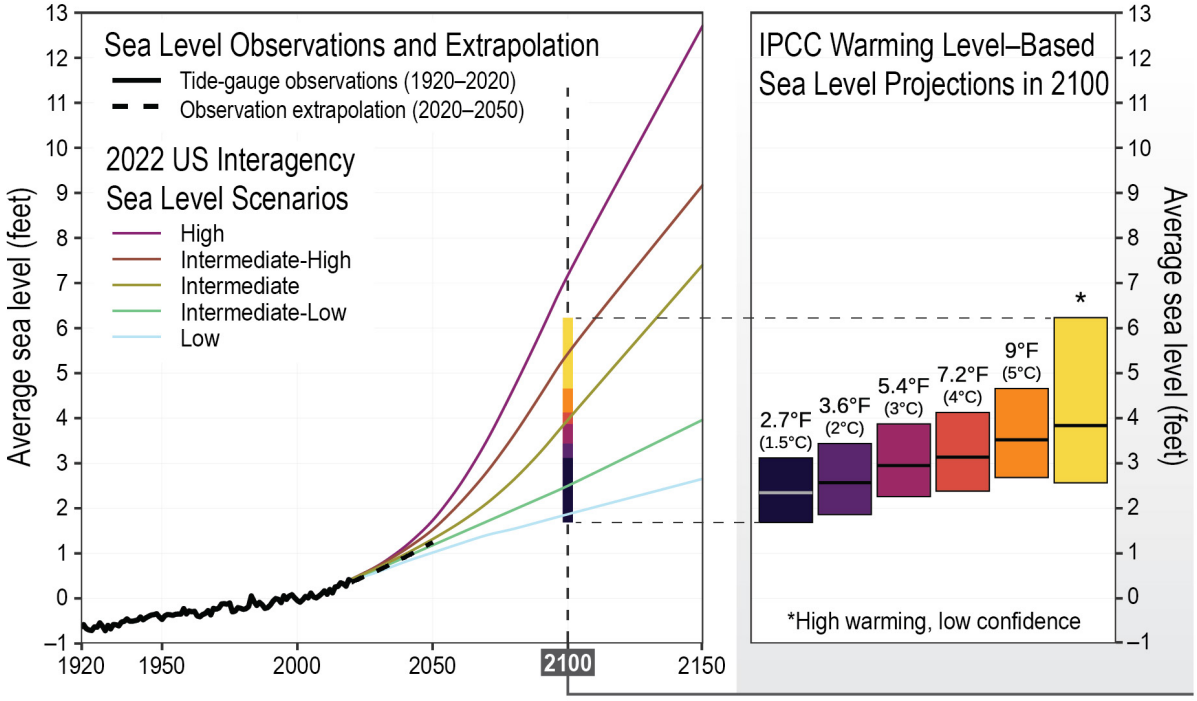
- Low, 1 foot (0.3 m) rise in global mean sea level relative to year 2000 baseline
- Intermediate-Low, 1.6 feet (0.5 m)
- Intermediate, 3.3 feet (1.0 m)
- Intermediate-High, 4.9 feet (1.5 m); and
- High, 6.6 feet (2.0 m) (Figure 9.1)

The SLR scenarios are downscaled to local and regional levels, considering future changes in land elevation, ocean heating and circulation, and Earth's gravitation and rotation from melting of land-based ice. They are constructed directly from the IPCC Sixth Assessment Report (AR6) emissions- and temperature-based projections (App. 3.3)[20] but use consistent framing (e.g., Sweet et al. 2017[21]) to support risk reduction planning.

Sea levels are rising along contiguous US coastlines faster than the global average, with about 11 inches (28 cm; *likely* range of 10–12 inches [25–30 cm]) occurring over the last 100 years (1920–2020) and with about half of this rise (5–6 inches [13–15 cm]) occurring in the last 30 years (1990–2020; Figure 9.1).[2] SLR rates vary across different regions. In the last 30 years, the greatest rise is observed along the US western Gulf Coast (about 9 inches [23 cm]), largely due to high rates of land subsidence[22] from subsurface groundwater and fossil fuel withdrawal.[23] About 6 inches (15 cm) of rise is observed along the northeast and southeast

Atlantic and eastern Gulf Coasts. Lower rates of rise are observed along the Hawaiian and US Caribbean island coastlines (4 inches [10 cm]) and the northwest (2 inches [5 cm]) and southwest (3 inches [8 cm]) Pacific coastlines.[2]

Accelerating Relative Sea Level Rise in the Contiguous US



Sea level is projected to continue to increase this century by amounts related to future global warming levels.

Figure 9.1. This figure shows accelerating sea level rise (SLR) trends and SLR scenarios along the contiguous US coastline. It also shows the relationship between projected SLR under different global surface temperature increases in 2100 (KM 2.2). The **left panel** shows observed increasing average sea levels during 1920–2020 (solid black line), an extrapolation out to 2050 based on observed sea levels over 1970–2020 (dashed black line), a range of scenarios describing plausible sea level rise out to 2150 (multicolored lines), and an overlapping stacked bar showing a range of projected changes in 2100 SLR under different levels of global surface temperature increase, based on the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. The **right panel** shows expanded versions of the projections shown in the stacked bar in the left panel. Black lines indicate the median value, the bars show the extent of the *likely* range (17th–83rd percentile) of SLR by 2100, and the associated warming levels are indicated above each bar. The "High warming, low confidence" case (yellow bar) refers to the potential range of rising seas under higher temperatures with rapid ice melt. The lack of overlap in 2100 between the High sea level scenario and the "High warming, low confidence" case in 2100 is not an indication of overestimation but rather a result of how the low-confidence processes are analyzed. Adapted from Sweet et al. 2022.[2]

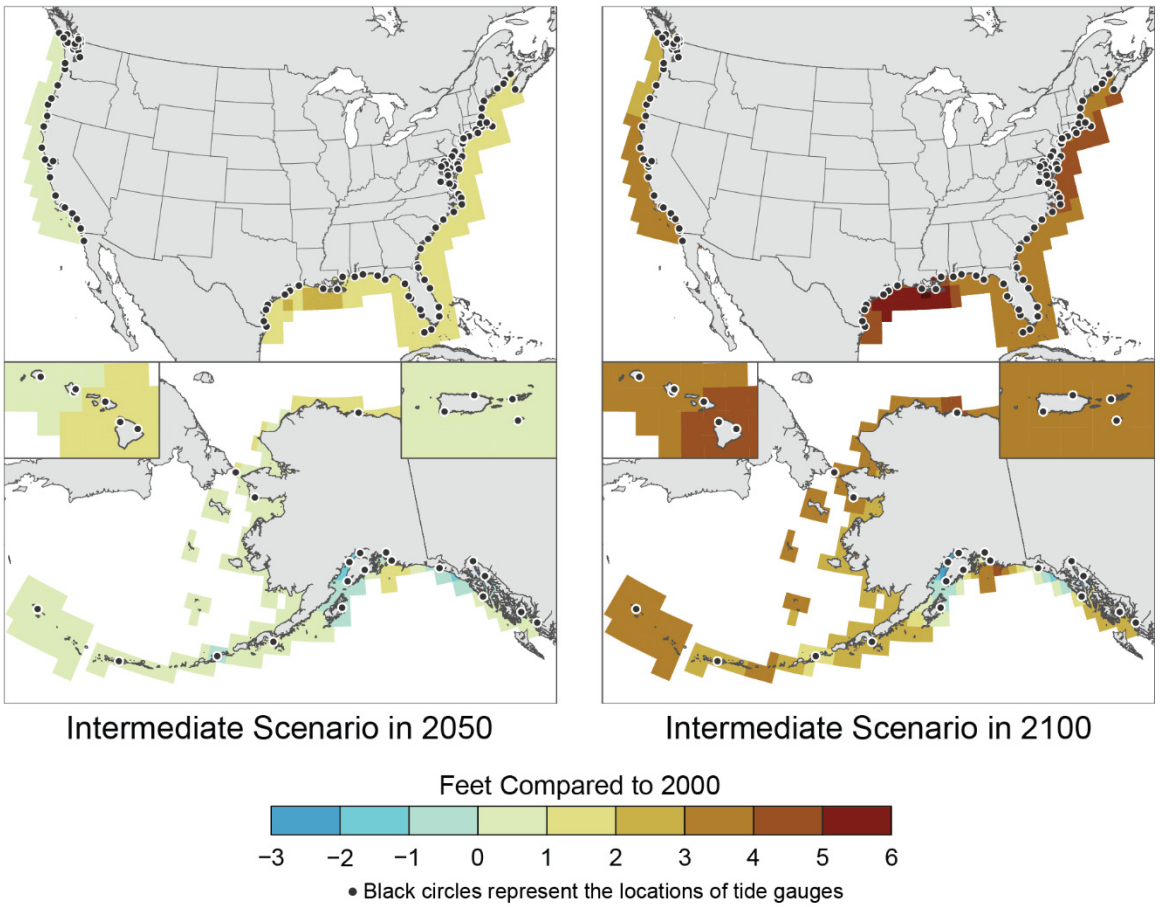
SLR rate suppression and acceleration along the northwest and southwest Pacific coastlines is in part due to oceanographic forcings associated with the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).[24] Along the Pacific Coast, ENSO and PDO will continue to drive decadal variability in SLR, with rates that are above or below the global average.[24] The current rate remains higher than the global average.[24] Characterizing past (and future) rise for Alaska and the US-Affiliated Pacific Islands is complicated due to tectonic effects that cause both uplift and subsidence. Year-to-year changes associated with natural variability can also change the rates over different analysis periods, such as the 8–12-inch (20–30 cm) variability in sea levels that can occur along the Pacific Coast during different phases of the ENSO.[25,26,27]

Looking toward the future, an 11-inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020, with a *likely* range of 9–13 inches [23–33 cm]; see Table A1.2 in Sweet et al. 2022[2] for 2000 to 2020 offsets) based on an observation-based trajectory of SLR (Figure 9.1). An 11-inch (28 cm) rise by 2050 matches the observed average SLR along the contiguous US coastline over the last 100 years (1920–2020), representing ongoing SLR acceleration that falls between the Intermediate-Low and Intermediate sea level scenarios.[2] By 2050, SLR amounts will continue to vary geographically, with regional differences like those observed in the recent historic record (e.g., 1990–2020). For example, under the Intermediate sea level scenario, which closely aligns with most regional SLR trajectories,[2] SLR is expected to be higher along the Atlantic versus the Pacific Coast and greatest along the western Gulf Coast (Figure 9.2).

Beyond 2050, future global emissions and resultant ocean and atmospheric warming and ice sheet responses will determine future SLR. As of 2021, global temperatures have increased by 2° –2.2°F (1.1°–1.2°C) beyond preindustrial levels (KM 2.1) and are headed for a warming level of about 5.4°F (3°C) by 2100 under the current trajectory,[28] which is consistent with the IPCC AR6 intermediate and high scenarios (SSP2-4.5 and SSP3-7.0). With such warming, it is *likely* that the Intermediate-Low sea level scenario with 2+ feet (0.6+ m) of SLR relative to 2020 levels will be exceeded by 2100, and 3.6+ feet (1.1+ m) will be exceeded by 2150 (App. 3.3; Figure 9.1).[2]

Failing to curb future emissions increases the probability of SLR equivalent to the Intermediate sea level scenario or perhaps even higher, such as the Intermediate-High and High sea level scenarios associated with the IPCC very high scenario (SSP5-8.5) that includes the addition of rapid ice sheet melt or disintegration during this century.[20] The probability of this low-likelihood outcome increases with higher global warming levels.[29] Under the Intermediate to High sea level scenarios, an average SLR of about 3.6–6.9 feet (1.1–2.1 m) along contiguous US coastlines by 2100 and 6.9–12.5 feet (2.1–3.8 m) by 2150 relative to 2020 would occur (Figure 9.1; App. 3.3).[2] Under the Intermediate-High and High sea level scenarios, contributions from the Antarctic ice sheet dominate and reduce overall SLR differences across US regions (KMs 2.1, 2.3).[2] Beyond 2150, global (and US) SLR will continue for millennia due to the long-term effects of warming this century. About 7–33 feet (2–10 meters) of global SLR over the next 2,000 years is *likely* if temperatures warm by 3.6° to 5.4°F (2° to 3°C) above preindustrial levels by 2100, similar to conditions about 125,000 years ago.[20,30]

Projected Sea Level Rise



By 2050 and 2100 under the Intermediate sea level scenario, sea level rise is projected to be higher along the Atlantic versus the Pacific Coast and greatest along the western Gulf Coast.

Figure 9.2. The figure shows relative sea level rise along the US coastlines under the Intermediate sea level scenario of the US Interagency Sea Level Rise Task Force[2] for 2050 (**left**) and 2100 (**right**). Relative sea level rise for the contiguous US is shown on the top, and for Alaska, Hawai'i (left insets), and Puerto Rico (right insets) on the bottom. The black dots along the coastline indicate tide-gauge locations used to characterize past SLR. Characterizing past (and future) SLR for Alaska and the US-Affiliated Pacific Islands is complicated due to tectonic effects that cause both uplift and subsidence. Figure credit: NOAA National Ocean Service.

Increases in Flooding Frequency Will Continue

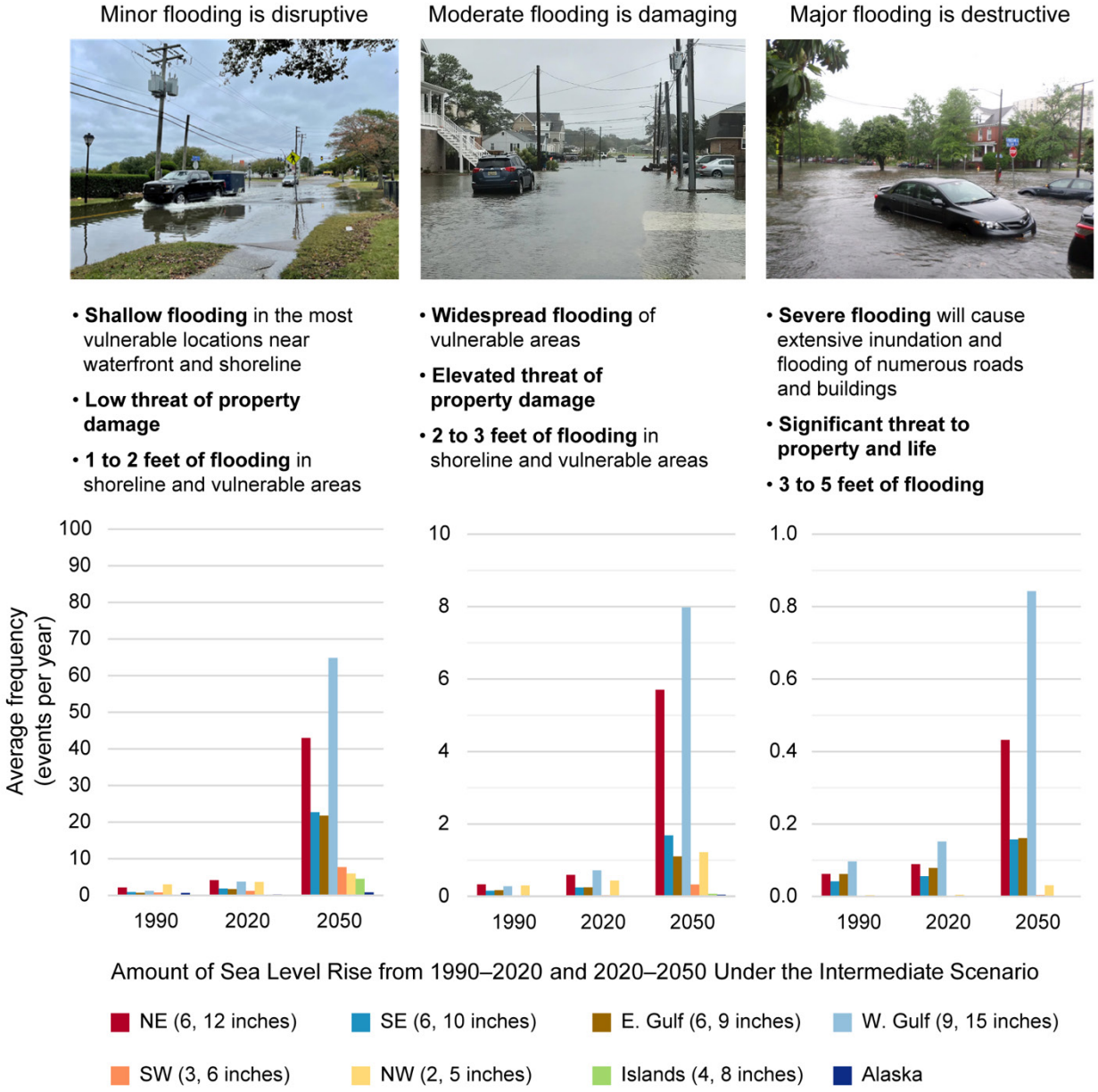
SLR will continue to cause permanent inundation for formerly dry lands and an escalation in the severity (depth, geographic extent, and frequency) of coastal flooding, ranging from powerful storm events to more frequent high tide flooding (HTF). As of 2020, the highest annual frequencies of coastal flooding—defined in a nationally consistent manner as minor (disruptive HTF, about 1.75–2 feet [0.5–0.6 m] above average high tide), moderate (damaging HTF, about 2.75–3 feet [0.8–0.9 m]), and major (destructive HTF, about 4 feet [1.2 m]) impacts[2,31]—are along the northeast Atlantic and western Gulf coastlines (Figure 9.3), due in part to greater exposure to strong storms and wide, shallow continental shelves allowing for higher storm surges.[32]

Annual frequencies of both minor and moderate coastal flooding increased by a factor of 2–3 along most Atlantic and Gulf coastlines between 1990 and 2020 (Figure 9.3). Minor HTF events, which are the most common impact of SLR, occur several times a year with accelerating frequencies (e.g., Sweet et al. 2019,[33] 2020,[34] 2021[35]). A typical HTF event lasts about two days and several high tides.[2] Along the coastlines of

Hawai'i, the US-Affiliated Pacific Islands, and US Caribbean islands, as well as some US Pacific coastlines, SLR is a growing problem. Flood impacts are occurring with much smaller flood heights than those shown in Figure 9.3, including in some cases where water levels are elevated only slightly above high tide.

By 2050 under the Intermediate sea level scenario (Figure 9.1), minor, moderate, and major coastal flood frequencies will all increase by a factor of about 5–10 in many regions relative to 2020 in the absence of adaptation (Figure 9.3). In effect, a flood regime shift would occur; for example, the frequencies of moderate flooding are projected to occur as often as minor, disruptive HTF occurs now (circa 2020). By 2100 under the Intermediate sea level scenario, major flooding would occur almost daily along US coastlines.[2] These increases in flood frequency could be further amplified with higher amounts of SLR, worsening storm conditions, natural climatic variability (e.g., ENSO), or other reasons such as long-term tidal cycles and land subsidence or uplift.[31,36]

US Regional Average Flood Frequencies



Minor, moderate, and major coastal flood frequencies will increase by a factor of about 5–10 in many regions of the US relative to 2020 in the absence of adaptation.

Figure 9.3. (**top**) Descriptions of three coastal flood types—minor (disruptive), moderate (damaging), and major (destructive)—provided by NOAA National Weather Service, reflect today's vulnerabilities within coastal communities. (**bottom**) These graphs show annual average frequencies of minor, moderate, and major flooding by region (multicolored bars). The flood frequencies are based on a set of 187 NOAA tide gauges, with 14 in Hawai'i and the US-Affiliated Pacific Islands, 4 in Puerto Rico, and 4 in the US Virgin Islands (collectively shown as Islands). Note that this figure uses the US regions defined in Sweet et al. (2022),[2] which differ from the NCA5 regions: NE = northeast Atlantic, SE = southeast Atlantic, NW = northwest Pacific, SW = southwest Pacific, E. Gulf = eastern Gulf, W. Gulf = western Gulf. Observations are shown for 1990 and 2020, and projections are shown for 2050 under the Intermediate sea level scenario for all US coastal regions. The amount of SLR for each region during 1990–2020 and 2020–2050 under the Intermediate scenario is provided below the graph. The amount of SLR for Alaska is not shown because Alaska's SLR varies along the shoreline due to both tectonic uplift and subsidence; the SLR values for Alaska are shown on Figure 9.2. The annual average frequencies of minor, moderate, and major flooding are projected to increase more in the next 30 years (2020–2050) than they did in the past 30 years (1990–2020) re-

gardless of any future worsening of storm events. In some Atlantic and Gulf Coast regions exposed to hurricanes, more severe and catastrophic coastal flood levels are possible and will become more likely as sea levels rise. Figure credit: NOAA National Ocean Service. Photo credits: (left) City of Norfolk Staff Photographer Andrew Cooper; (center and right) Jeff Orrock, NOAA.

Waves, Storminess, and Landscape Variability Amplify Flood Risk

Climate-driven changes to coastal water levels, including waves, storm surge, river flows, and landscape changes, are important considerations when planning for future flood risk.[37,38,39] Wave-driven water levels, for example, comprise 25%–90% of extreme coastal water levels along exposed US coastlines.[2,40,41] Across most US coasts, many extreme events are increasing in intensity, frequency, and geographic extent (KM 2.2) because of human-caused climate change (KM 3.1). For example, hurricanes are intensifying more rapidly and decaying more slowly, leading to stronger storms extending farther inland with heavier rainfall and higher storm surges, resulting in less time for communities to prepare (KM 2.2). Climate change is also increasing coastal hazards through changes in the frequency, magnitude, and impacts of compound events (Figure 9.3; Focus on Compound Events).[42,43] In the coastal zone, compound flood events are commonly due to the joint occurrence of heavy precipitation, high river flows, elevated groundwater levels, soil saturation, and elevated ocean water levels.[38,44,45]

Key Message 9.2

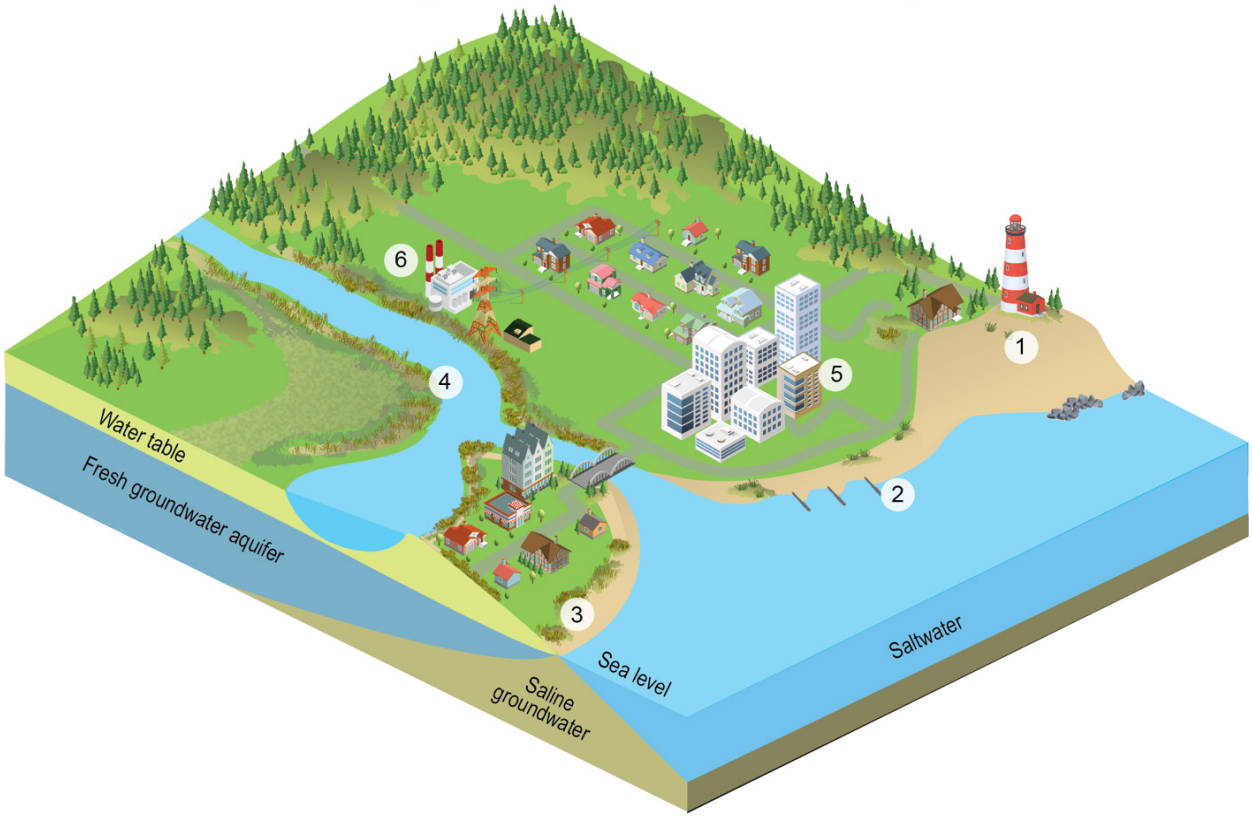
Coastal Impacts on People and Ecosystems Are Increasing Due to Climate Change

Climate change–driven sea level rise, among other factors, is affecting the resilience of coastal ecosystems and communities (*very likely*, *high confidence*). The impacts of climate change and human modifications to coastal landscapes, such as seawalls, levees, and urban development, are both limiting the capacity of coastal ecosystems to adapt naturally and are compounding the loss of coastal ecosystem services (*very likely*, *high confidence*). Proactive strategies are necessary to avoid degraded quality of life in the coastal zone, as the combination of reduced ecosystem services and damage to the built environment from exacerbated coastal hazards increasingly burdens communities, industries, and cultures (*very likely*, *high confidence*).

On the coast, natural landscapes are intertwined with the cultures, economies, and built infrastructure of humans (Figure 9.4). Coastal landscapes (e.g., beaches, dunes, barrier systems, coastal wetlands, and cliffs) evolve across a range of timescales (from minutes to millennia) in response to physical forcing (e.g., tides, waves, storms, climate variability), as well as biological (e.g., vegetation type and density, ecosystem characteristics) and geological (e.g., sediment flows, tectonics, substrate composition) controls.[46] Climate change is exacerbating coastal hazards, with rising seas and more intense storms leading to increases in both flood risks and shoreline change and erosion (KM 9.1).[47,48,49,50]

Coastal communities face heatwaves, heavy rainfall, landslides, compound flooding, and other climate hazards that are not unique to coastal environments.[14] The health, function, and productivity of coastal ecosystems are also being degraded by stressors from human actions (e.g., development, dredging, wetland infill, sediment diversions). Combined, these threats jeopardize attachment to place,[51] economies, and safety (Figure 9.5).[52,53] Understanding the interactions and interconnections between hazards (KM 9.1), communities, and coastal ecosystems is necessary for taking informed action to mitigate and adapt to climate change (KM 9.3).

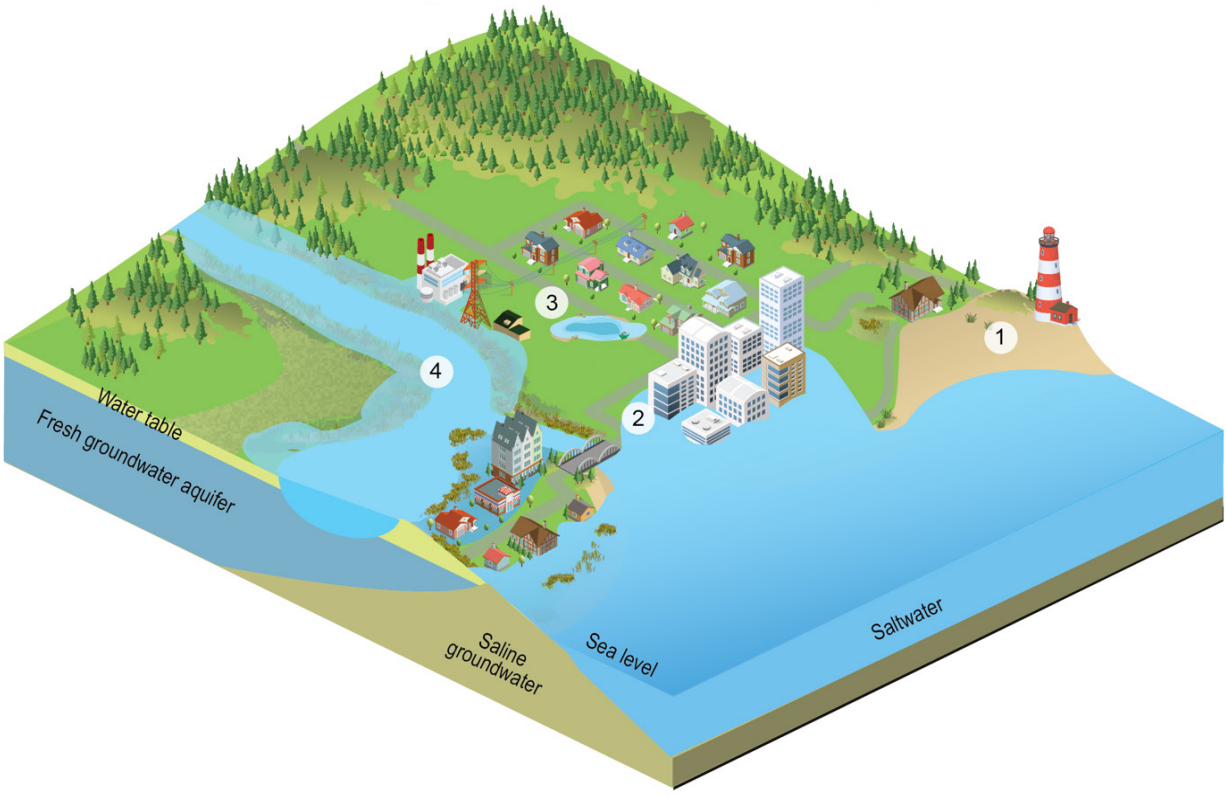
Existing Conditions in a Coastal Community



Coastal landscapes and man-made interventions provide economic, cultural, and community protection from existing climate hazards under existing conditions.

Figure 9.4. This hypothetical coastal community shows some of the natural and built environments found in our Nation's actual coastal communities. This community has several types of open coast shorelines, including 1) cliffs, 2) low-lying beaches, and 3) a barrier island. Behind the barrier island is 4) a tidal estuary fringed with marshes. There are two residential neighborhoods, 5) a commercial hub, and 6) an industrial zone that is water dependent. The riprap at the cliff base and beach groins (narrow perpendicular structures extending from the beach into the ocean) provide protection from coastal erosion due to waves. Subsequent figures in this chapter will illustrate the possible impacts of climate change on this community (Figure 9.5) and adaptation strategies to increase its resilience (Figure 9.6). Adapted from Dupigny-Giroux et al. 2018.[54]

Increasing Hazards in a Coastal Community



Coastal communities are expected to flood due to rising sea levels and rising groundwater levels.

Figure 9.5. Future climate impacts to our coastal landscapes and communities will be variable. 1) Increased sea level and wave energy will result in shoreline erosion and the collapse of coastal cliffs, which can alter iconic landscapes and damage places of value, including historical or cultural sites. 2) Flooding and wave hazards, including 3) flooding from higher groundwater tables, are anticipated, threatening homes and businesses as well as infrastructure and utilities. 4) Some ecosystems may be able to adapt or migrate to keep pace with future sea levels, and others may become inundated and converted to open water. Adapted from Dupigny-Giroux et al. 2018.[54]

Impacts on Communities and People

Our Nation's coasts underpin substantial sectors of our economy, serving as the entry and exit for goods and services (Focus on Risks to Supply Chains), generating revenue through recreation and tourism, and supporting thriving and diverse fisheries and other water-based industries. Coastal counties contribute $11 trillion annually (in 2022 dollars) in goods and services and employ 58.3 million people.[8] Increasing impacts to coastal systems due to exacerbating hazards will ripple across the US.

As extreme storms intensify and/or the impacts are exacerbated by SLR (KMs 2.2, 3.5), damages are increasing by the billions, with significant damage centered where tropical cyclones (e.g., hurricanes) make landfall[55] and where extratropical cyclones are the more common driver of coastal hazards.[48,56] Extreme storms and more frequent high tide flooding (HTF) bring cascading impacts, including loss of energy accessibility and continuity (KM 5.2); loss of ecosystem services (KMs 8.1, 8.3); impacts to agriculture from flooding and saltwater intrusion into groundwater (KM 30.1); flooding, erosion, and landslide disruptions to transportation (KM 13.1), utilities, infrastructure, emergency services, and teleconnections (KM 12.2); and population migration and displacement (KM 20.3).

Coastal hazard assessments that consider SLR, storm surge, waves, rainfall, and coastal change (e.g., beach and dune change, cliff change) can better depict potential future coastal response and societal impacts.[37,57,58] Compared to assessing only SLR-driven flooding, including these processes greatly expands the floodplain region in the northern Gulf of Mexico[58] and triples the estimated number of people on the Pacific Coast exposed to flooding.[37]

During an extreme event, more ocean water can wash over barrier islands and flow into bays via inlets, enhancing flood risk and amplifying storm surge within inland coastal bays by more than 20%.[59,60,61] Continued population growth and urbanization will expose an ever-increasing number of people to coastal flood risks.[3,62,63,64]

Although extreme storm events make newspaper headlines, SLR brings chronic challenges that could be equally or more damaging over the long term.[2] Coastal groundwater investigations in Pacific Island settings,[65] low-lying atolls,[66] karst aquifers,[67] barrier island systems,[68] and active tectonic margins[69,70] have demonstrated that climate-driven groundwater rise will impact coastal communities and ecosystems due to saltwater intrusion into groundwater sources, more saturated soils, and ponding at the surface comparable in magnitude to SLR-driven overland flooding. Seawater intrusion into coastal aquifers can increase salinity beyond potable levels, endangering access to fresh water for millions of people.[71]

The combination of rising groundwater and HTF in coastal communities will continue to impact stormwater and wastewater infrastructure, including septic systems, and increase the occurrence of urban flooding.[72,73,74,75,76] This could cause public health concerns, such as pollutant discharges into the environment[77] and the spread of environmental infectious diseases (KM 15.1). Additionally, contaminated sites, such as Superfund sites, face increasing exposure to rising groundwater and flood damages, which could lead to future public health and environmental concerns if buried contaminants are mobilized and enter groundwater or river systems (KM 28.2). HTF and rising groundwater will also increase occurrences of roadway flooding, potentially impeding traffic, delaying emergency response efforts, flooding properties, and negatively impacting real estate values and commerce.[78,79,80,81,82] In agricultural areas, rising groundwater and saltwater intrusion in irrigation systems are reducing crop productivity, resulting in barren farmlands in the absence of salt-tolerant crops.[83,84]

The impacts of worsening coastal hazards are not equally distributed across US communities (KM 20.1; Box 20.1).[85,86,87] Disparities in wealth, economic and educational opportunities, infrastructure quality and quantity, and investment in flood risk-reduction measures all contribute to variable physical and socio-economic impacts on coastal residents.[88,89,90] Many Tribal and Indigenous communities face severe impacts from extreme storms, erosion, permafrost thaw, and SLR, with limited resources to support adaptation (KMs 16.1, 29.4, 29.7; Ch. 30). Historic redlining policies forced communities of color into the least valuable, often low-lying lands that have increased flood risks, higher exposure to toxic substances, and more climate change–exacerbated hazards than non-redlined neighborhoods.[91,92,93] Communities that are economically disadvantaged have a higher statistical risk of flood exposure than wealthier communities.[86,87,88] This inequity is further increased because the impact of coastal flooding on individuals and communities is not only based on flood damages but also the ability to pay for the costs of recovery.[85] Decades of limited community inclusion in decision-making and disinvestment in critical infrastructure and community services have generated greater risk to physical and socioeconomic impacts of coastal hazards.[94]

In addition to direct impacts from acute events, chronic impacts are also experienced unequally among coastal residents. Changes in ecosystem services such as fisheries habitats will impact Indigenous practices in which culture and biodiversity are inextricably linked. In the Hawaiian Islands, *loko iʻa* (Hawaiian fishponds) are low-intensity forms of aquaculture that traditionally provided food security, contributing to coastal community resilience (KMs 30.1, 30.5).[95,96] These systems are threatened by SLR, with consequenc-

es on local livelihoods and cultural practices. Other communities, such as subsistence fishers and fisheries-based rural villages, will similarly suffer as negative impacts on coastal fisheries habitat threaten their way of life (KMs 10.1, 10.2).

The steady rise in flood insurance prices reduces home affordability in coastal regions, with many heirs and low-income and moderate-income property owners unable to afford flood insurance (KMs 16.1, 21.5).[97,98] Aside from home affordability, cascading effects such as climate gentrification—when affluent residents move into low-income areas less exposed to climate hazards, displacing the previous residents[99,100,101]—and lack of workforce will continue impacting culture, diversity, and economic productivity in coastal areas.[99,102,103,104]

Natural Resilience of the Coast Is Changing

For centuries, humans have been reshaping the coast to meet societal needs through urban development, sediment retention and diversion, and coastal defense structures.[105,106,107] These interventions have driven many coastal systems dangerously close to irreversible and profound change (KM 8.1).[108,109] Ecosystem losses due to erosion, more frequent flooding, and coastal squeeze (where human development or natural elevation change limits or prevents inland migration of coastal habitats) will increasingly limit the capacity of coastal landscapes to adapt naturally and diminish their ability to provide valuable ecosystem services (Figure 9.5; KM 8.1).[47,110,111,112,113]

Mangroves and salt marshes, collectively referred to as tidal wetlands, provide culturally and economically essential fisheries habitat and absorb and store floodwaters (Focus on Blue Carbon).[114,115] SLR and increasing coastal hazards (KM 9.1), as well as eutrophication, sediment availability, poor drainage, and coastal squeeze can all drive tidal wetland loss.[116,117] Some tidal wetlands may survive in place due to accretion, while others may migrate upland and convert other ecosystems (e.g., upland habitat, agriculture, and forests) into tidal wetlands.[118,119]

Throughout the US, a net loss of tidal wetlands is expected, but the rate and extent to which the loss occurs will vary significantly by geography and climate change scenario.[120] For example, in Chesapeake Bay,[121] Florida,[122] and New Jersey,[117] a net loss of tidal wetlands is expected. Along the Gulf Coast, mangroves are overtaking salt marshes, reflecting a shift in vegetation dynamics and habitat.[123] Coastal development and steep topography limit inland migration along the Pacific Coast, and tidal wetland conversion to open water and net tidal wetland loss due to SLR appear inevitable.[124]

Barrier islands and reef systems act as a first line of flood defense, absorbing wave impacts as large storms make landfall, thereby reducing flood risk for coastal and inland communities.[125,126,127,128,129] Barrier island and mainland beach systems may migrate landward naturally to keep pace with SLR, or they may be outpaced and narrow and/or flatten depending on their elevation, how frequently storm waves wash over them, sediment supply, and the persistence of vegetation, all of which can be affected by human modifications.[61,130,131,132,133,134,135]

Long-term observations, projections of coastal change and erosion, and improved understanding of complex coastal feedback processes help define the conditions and tipping points that may limit natural adaptation (KM 8.1).[136,137] Climate adaptation that restores natural processes and works with coastal ecosystems and landscapes may reduce flood risks while providing multiple co-benefits, including carbon sequestration (KM 8.1; Focus on Blue Carbon). For example, acquired or restored open-space areas (e.g., undeveloped, agricultural, or park lands) along the coast can provide accommodation space for inland wetland and coastal habitat migration as seas rise.[138,139]

Allowing coastal ecosystems to evolve naturally may negatively impact some communities and wildlife species, such as the reshaping of barrier islands in response to extreme events that can increase inland storm surge (KM 9.1); however, these natural changes may have beneficial impacts for other species and communities through habitat creation and water quality improvements.[50,134] All changes across the landscape have implications for changes to biodiversity via species declines, species range and phenological shifts, disease, and impacts from invasive species (KM 8.2), affecting seagrasses, corals, mangroves, fisheries, shorebirds, and marine mammals (KMs 21.2, 22.1, 23.2, 26.3, 27.3, 28.2, 30.4).

Key Message 9.3

Adaptation Reduces Risk and Provides Additional Benefits for Coastal Communities

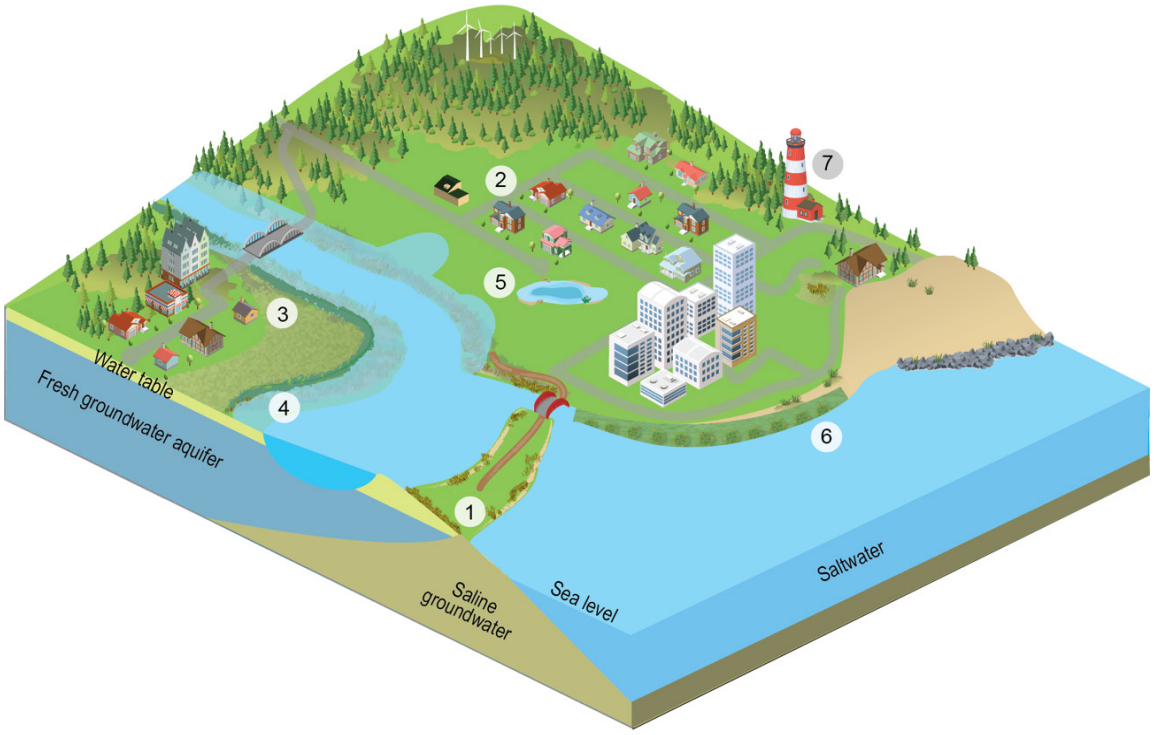
Accelerating sea level rise and climate change will transform the coastal landscape, requiring a new paradigm for how we live with, or adapt to, these changes (*high confidence*). Although incremental in nature, nature-based solutions and planned relocation strategies may help communities adapt to increasing coastal hazards if they are community-led and equity-centered (*medium confidence*). Maintaining cultural and economic connections within coastal communities will require equitable transformative adaptation that addresses systemic interconnections between ecosystems, communities, and governance (*medium confidence*).

Despite projected climate change impacts, coastal communities remain valued places for living and working. Relentless growth in, and enthusiasm for, the coast creates a tension between the need to adapt to climate change and our existing relationships with the coast.[14,140] Although adaptation is occurring in some locations, small-scale and incremental adaptations are not sufficient for the pace and scale of changes that are already occurring (KMs 9.2, 31.1).[13,14,15] Accelerating SLR and increasing coastal hazards (KM 9.1) are affecting larger geographic areas along the coast, expanding the scale and complexity of the adaptation responses and the number and diversity of stakeholders at risk.[13]

Adaptation that includes a broad suite of strategies that address the root causes of coastal vulnerability, consider the needs of diverse stakeholders, center equity (KM 31.2), and reframe societal values and assumptions can lead to transformative and systemic change that can allow coastal communities to thrive and maintain a relationship with the coast (KMs 22.1, 31.3).[141] Example strategies can include updated land-use policies,[142,143] community infrastructure investments, nature-based solutions (NBSs), and planned relocation.[14,144] Individually, these strategies are incremental steps, but when combined in a manner that considers long-term community goals and inclusive and sustained engagement with frontline communities, they can lead to equitable transformative adaptation (Figures 9.6, 22.6, 31.3; Box 9.1; KMs 31.2, 31.3).[14,145]

Transformative adaptation requires fundamental shifts in systems, values, and practices to equitably address the risks of climate change (KM 31.3), including integration of local perspectives, which leads to more equitable distribution of resources.[9] Community-led adaptation actions and NBSs can also enhance a sense of place by recreating lost relationships with the coast or fostering new ones between people and the environment.[14]

Adaptation Strategies for a Coastal Community



Timely implementation of adaptation strategies, including planned relocation, can reduce the impacts of climate change on coastal communities.

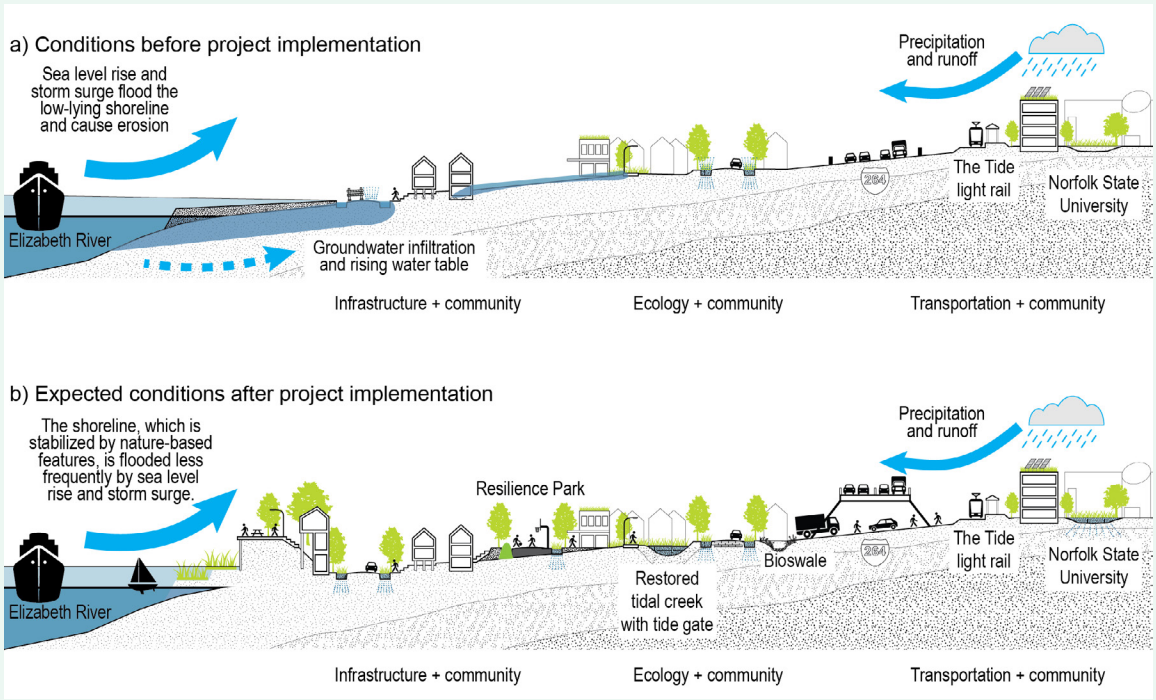
Figure 9.6. Many strategies can reduce climate-driven coastal hazards. 1) Critical infrastructure, housing, and businesses can relocate out of harm's way. Retreated lands create space for parks and recreational areas, nature-based solutions (NBSs) for flood risk-reduction, or migration space for coastal ecosystems, while also accommodating rising waters. 2) Relocated communities may move into established communities, or 3) they may create new residential centers. Intentional and equitable stakeholder engagement helps ensure that historic inequities are not perpetuated during relocations. 4) NBSs, such as restoring wetlands, can slow and store rising waters. 5) Housing and structures can be relocated away from rising groundwater tables. 6) Combinations of green and gray infrastructure (hybrid strategies) may be required; for example, a living seawall provides shoreline protection and beneficial habitat for marine organisms. 7) Cultural assets that define a community's character, such as this lighthouse, can be elevated or moved. Adapted from Dupigny-Giroux et al. 2018.[54]

Box 9.1. On the Road to Adaptation: Norfolk, Virginia

Norfolk, Virginia, home to 245,000 residents and the world's largest naval complex, lies at the mouths of the James and Elizabeth Rivers and Chesapeake Bay. The rate of sea level rise is currently about 0.2 inches (4.7 mm) per year and accelerating. Today, high tide flooding (HTF) occurs 10–15 times annually and by 2050 could occur 85–125 times per year on average.[2,146] Large-scale resilience projects that feature nature-based solutions (NBSs) are under construction as a result of citizen-led strategies that informed the city's land use, regulations, and investments.[147]

The Ohio Creek Watershed Project, funded by a $112 million National Disaster Resilience Competition grant, addresses HTF, storm flooding, and shoreline erosion that caused community isolation and fragmentation (Figure 9.7). The neighborhoods are predominantly Black and include a public housing development and hundreds of homes on the National Historic Register. An extensive community involvement process made sure that residents from the impacted neighborhoods were heard and that societal challenges would be addressed. The project's centerpiece is Resilience Park, including a restored tidal creek and flood berm, wetlands, and NBSs. Surrounding neighborhoods will have accessible roads during HTF events and gain community gathering spaces and places for work and play.

Present and Future State of the Ohio Creek Watershed



Strategies that consider long-term community goals and inclusive and sustained engagement with frontline communities can lead to equitable transformative adaptation.

Figure 9.7. By centering the concept of community, neighborhoods will receive shoreline protection to address sea level rise and higher storm surge, updated infrastructure to address rising groundwater and increasing precipitation and runoff, a large gathering space known as Resilience Park, and accessible transportation for people and vehicles. This example of transformative adaptation involves traditional engineering projects and nature-based solutions. Adapted with permission from Waggonner & Ball ©2022.[148]

Nature-Based Solutions in Coastal Communities

NBSs integrate natural processes with traditional engineering approaches to reduce flood risk while also preserving or enhancing the ecological value of natural landscapes (e.g., maintaining essential habitat for protected species) and providing potential societal, economic, and other co-benefits (Focus on Blue Carbon).[149,150] NBSs can include ecosystem conservation and restoration or recreation of natural processes that reduce flood risks, hybrid solutions (e.g., living shorelines), and the greening of traditional infrastructure (e.g., ecological riprap).[151,152] Although NBSs are effective in reducing temporary flooding resulting from storms, they may provide only modest benefits in preventing permanent inundation from SLR.[149,153] However, when NBSs are paired with planned relocation, protection from flooding and SLR is provided by moving a community out of harm's way while also reestablishing the natural flood risk-reduction benefits of coastal ecosystems.[52]

Mangroves and other coastal wetlands reduce wave energy,[154,155] decrease coastal erosion,[156,157] and provide flood attenuation.[114,158,159] Wetlands helped communities avoid $795.2 million (in 2022 dollars) in direct flood damages during Hurricane Sandy.[127] Beaches and dunes reduce storm surges and absorb wave energy.[160] Coral reefs damp wave energy and provide flood protection for adjacent communities, with an estimated flood risk-reduction benefit of over $2.2 billion annually (in 2022 dollars) in the contiguous US[161,162] and more than $1.1 billion (in 2022 dollars) annually in Hawai'i, Guam, American Sāmoa, the Commonwealth of the Northern Mariana Islands, Florida, Puerto Rico, and the US Virgin Islands.[163]

Hybrid solutions can reduce shoreline erosion[164,165] and enhance the engineering design life and flood risk-reduction performance of traditional infrastructure.[166] Flood risk-reduction benefits of hybrid solutions have been demonstrated across varying hydrodynamic conditions.[165] NBS guidance documents[149,167,168,169] are continually published, and implementation of NBS strategies is increasing. The ability to include adaptive elements in NBSs for future changing conditions[144,170,171] makes them an important component of the adaptation landscape over the coming decades.

Planned Relocation Strategies in Coastal Communities

Planned relocation is the process of moving individual properties, infrastructure, or whole communities preemptively away from, or in response to, the impacts of natural hazards.[172] Historically, most communities have remained in place post-disaster by adapting or rebuilding using engineered solutions (KM 20.3).[173] However, as climate change impacts increase, adapting and rebuilding in place will become more challenging (KM 31.1). With accelerating SLR, particularly under low-likelihood, high-impact SLR scenarios (Figure 9.1), planned relocation may become more cost effective than adapting in place, with a lower long-term risk of loss of life and property if engineered solutions fail.[174]

In the US, planned relocation generally occurs reactively (i.e., post-disaster) rather than proactively (i.e., relocating at-risk communities before a disaster). For example, targeted buyouts of assets most at risk of future repetitive damage occurred after Hurricane Sandy in Staten Island, New York.[175] Residents and communities have also relocated after natural disasters, such as Isle de Jean Charles, Louisiana;[176] Kivalina, Alaska;[177] and the Quinault Indian Nation (Box 20.1). As planned relocation expands, there is an urgent need to assess lessons learned from past relocations and lean into transformative adaptation that improves community well-being and addresses social, ecological, and intergenerational justice.[178,179]

Proactive planned relocation may become the most viable response for many future coastal communities as SLR continues and coastal lands become submerged.[38,180] However, discussions of planned relocation remain challenging and controversial.[12,174] Impediments include resistance to change;[181] disagreements about when communities and infrastructure may be irrevocably lost and, thus, the appropriate timing for relocation; lack

of community-led decision-making; cost effectiveness compared to defending in place;[174,182] disruptions to community cohesion and social capital;[183,184] and identification of suitable replacement locations.[185]

Transformative Adaptation Opportunities in Coastal Communities

Transformative adaptation that is proactive and intentional and involves fundamental shifts in systems, values, and practices (KM 31.3) provides opportunities to meet the challenges of shifting and receding shorelines. Transformative adaptation along the coast considers aspects such as funding and economic security, alignment of governmental entities, attachment to place and livelihoods, and technical expertise.[52,53]

Intentional and equitable transformative adaptation is an opportunity to redress root causes of inequities and disparate impacts of climate change in coastal communities.[14,15] Achieving this would require sustained funding dedicated to proactive planning, design, and execution.[186] This would prevent reactive strategies that have historically exacerbated inequities and focused resources on wealthy, typically White communities (KM 20.3)[187]—a particular challenge in areas where there are large disparities in wealth and where lower-income homeowners and renters lack affordable flood insurance.[103]

Current adaptation strategies that are increasingly being implemented on the coast could shift toward transformative adaptation if local communities are centered and inequities are transparently addressed (KMs 31.2, 31.3; Figure 31.2). This will require an incremental shift in practice, resulting in additional shifts in systems (e.g., permitting), values (e.g., recognizing and addressing past injustices), and risk tolerance (e.g., increasing comfort in natural shoreline protection over more traditional hardened structures).

Traceable Accounts

Process Description

This assessment builds upon and amplifies the Key Messages within the "Coastal Effects" chapter of the Fourth National Climate Assessment, as those Key Messages are still relevant, yet they have become even more urgent.[188] The US Interagency Sea Level Rise Task Force's (hereafter "Task Force") report[2] provides clear evidence that sea level rise (SLR) is already accelerating and that current SLR tends are tracking on the Intermediate-Low curve or higher along the Nation's coasts.

Impacts associated SLR and extreme coastal storms are increasing per observations, coastal ecosystems and communities are facing increasing risks, and transformative adaptation grounded with nature-based solutions may provide our best hope to retain a sense of balance between the coasts and our coastal communities. The author team required a depth and breadth of expertise across the Atlantic, Gulf, and Pacific Coasts, as well as the coastlines of Hawai'i and the US-Affiliated Pacific Islands, the US Caribbean, and Alaska; the leading edge of SLR science; the physical processes that shape our coastlines; the systemic inequities that continue to put frontline communities at greatest risk; and the human actions that have altered the coasts and transformed the shoreline to suit societal desires.

Prospective authors were nominated by their respective agencies, universities, organizations, or peers. The chapter lead and federal coordinating lead authors discussed and vetted prospective authors with a goal of creating a cohesive author team committed to bringing their formidable experience and skillsets together to develop this chapter.

This chapter was developed through weekly teleconferences, email exchanges, technical discussions of the relevant evidence base, and expert deliberation by the authors. The author team, along with the US Global Change Research Program, held a public engagement workshop with participants from federal, state, and local agencies; consultants; and interested members of the public. The workshop used innovative approaches and breakout groups that explored what the participants loved most about the coast before diving into the key topics that framed this chapter and the development of the Key Messages.

The urgent need for adaptation, with an emphasis on nature-based solutions and planned relocation, was a clear driver for Key Messages 9.2 and 9.3. Additional literature is required that presents lessons learned and successful implementations, even if at a small scale, to achieve the scale of planned relocation that is expected to be required in the US over the next century.[179] The authors extensively reviewed the literature on transformative adaptation and adaptation that centered equity, community values, and included strong community participation. The concept of transformative adaptation and planned relocation required dialogue across many chapters, with an emphasis on Chapter 20 (Social Systems and Justice) and Chapter 31 (Adaptation) to achieve consistency and portray a sense of urgency for the Nation along these paths.

Consensus on the Key Messages and supporting literature required multiple iterations, discussions with other chapters, and careful review and revisions in response to comments from the public and the National Academies of Sciences, Engineering, and Medicine.

Key Message 9.1

Coastal Hazards Are Increasing Due to Accelerating Sea Level Rise and Changing Storm Patterns

Description of Evidence Base

Multiple lines of evidence, including satellite and tide-gauge observations and model simulations, show that substantial SLR has occurred to date, globally and for the US, as documented and synthesized in the Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6) and the Task Force report on SLR.[2,189] Observations show that SLR is accelerating at global, national, regional, and local levels, and AR6 projections and the sea level scenarios from the Task Force report suggest that these trends are expected to continue over the next several decades and through the end of this century and beyond (see https://sealevel.nasa.gov/data_tools/18).[2,189] Beyond 2150, SLR is expected to continue for the next several thousand years due to the long-term effects of emissions and warming over this past century, irrespective of future emissions occurring after 2100. These lines of evidence are synthesized, and a large body of relevant literature is documented (e.g., Dangendorf et al. 2019;[190] Frederikse et al. 2020;[191] Fox-Kemper et al. 2021;[20] Hamlington et al. 2021;[192] Edwards et al. 2021[193]), in the Task Force report on SLR[2] and IPCC AR6.[189]

An additional body of literature and references therein links this increase in average sea level to a broad range of risks and adverse impacts in the coastal zone. Extreme water levels will continue to rise with SLR, causing deeper, more frequent, more severe, and more widespread flooding (e.g., Sweet et al. 2021,[35] 2022;[2] Taherkhani et al. 2020;[194] Thompson et al. 2021;[36] Vitousek et al. 2017[41]). Observational and model simulation evidence also indicates that many types of extreme events are increasing in intensity, frequency, and geographic extent as a result of human-caused climate change and that hurricanes, in particular, are intensifying and causing heavier rainfall and higher storm surges, all of which compounds these flood risks (see evidence base underlying Key Messages 2.2 and 3.6 and USGCRP 2017[195]). Extreme water levels and flooding lead, in turn, to additional coastal zone impacts (e.g., erosion, damage to property and infrastructure, ecosystem impacts). Compound flooding associated with other coastal storm types (e.g., atmospheric rivers, extratropical cyclones) is also projected to increase with a warming climate.[196,197,198]

A further body of literature documents how population growth, migration, and development trends in the coastal zone have exacerbated societal risks and exposure of populations and the built environment to increasing SLR- and flooding-related hazards.[199,200,201]

Major Uncertainties and Research Gaps

For near-term impacts (to 2050), uncertainties and research gaps include the impact of natural climate variability on the observation-based trajectories, coastal adaptation, and policy actions to reduce future hazards and improved incorporation of interacting and compounding drivers into projections of coastal water levels and overall coastal flood hazards, such as winds, surge, waves, rising water tables, and extreme rainfall. In addition, more detailed understanding of, and data on, compound flood hazards is a key area of research needed to better understand and communicate flood risks and inform adaptation efforts.

For longer-term impacts (after 2050), major uncertainties and research gaps include improved modeling and observational capabilities to assess long-term global average SLR trajectories as a function of uncertainties in both emissions pathways and the sensitivity of ice sheet dynamical processes to a given level of warming, particularly the "low-confidence" ice sheet processes, as per IPCC AR6.[20] Projections that include these ice sheet processes, particularly under higher-emissions futures, result in substantially higher global average SLR values by the end of this century and beyond. Pathways to such futures include outcomes

such as earlier-than-projected ice shelf disintegration in Antarctica; abrupt, widespread onset of marine ice sheet instability and/or marine ice cliff instability in Antarctica; and faster-than-projected changes in surface-mass balance on Greenland, potentially associated with changes in atmospheric circulation, cloud processes, or albedo changes.[2] Monitoring the sources of ongoing SLR and the processes driving changes in sea level is critical for assessing scenario divergence and tracking the trajectory of observed SLR, particularly during the period when future emissions pathways might increase the risk of triggering these low-confidence processes.

Description of Confidence and Likelihood

Based on a spatially weighted average of about 100 NOAA tide gauges and following methodologies in Sweet et al. (2022),[2] there is *high confidence* that sea levels along the contiguous US have risen about 11 inches (*likely* range between 10 and 12 inches) on average over the 1920–2020 period, with about 5–6 of those inches occurring since 1990, indicating that sea level rise is accelerating. There is also *high confidence* that the probability of minor, moderate, and major coastal flooding increased by about 2–3 times between 1990 and 2020 (as defined by contemporary NOAA weather-related impact thresholds calibrated to historic NOAA tide-gauge water level heights). Thus, it is *very likely* that the severity and risks of hazards are increasing.

There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (*likely* range of about 9–13 inches) between 2020 and 2050 based on both extrapolating rates and accelerations estimated from historical tide-gauge observations and model projections, with both approaches producing projections within similar ranges. In response to 11 inches of SLR by 2050, there is *high confidence* and it is *very likely* that the probability of minor, moderate, and major coastal flooding will occur 5–10 times more often by 2050 in many regions without additional flood risk-reduction measures, as compared to contemporary standards.

Key Message 9.2

Coastal Impacts on People and Ecosystems Are Increasing Due to Climate Change

Description of Evidence Base

A growing body of literature captures the limited ability of coastal ecosystems to adapt to climate-driven changes, particularly due to human modification. Multiple lines of evidence show that physical changes in the coastal zone in response to climate change are occurring, including upland conversion and marsh expansion,[121,122,202] expansion of mangrove systems,[123] and marsh and beach loss due to erosion and barriers that limit inland migration of these ecosystems.[47,50,110,119,138,203] The consequent loss of ecosystem services, such as storm protection, wetland carbon sequestration, sensitive habitat, and industry, including agriculture, tourism, recreation, and fishing, has been well documented (e.g., Siverd et al. 2020;[204] Weiskopf et al. 2020[205]), and the amplification of these losses via human modifications of the coast are well supported in the peer-reviewed literature.[105,113,206]

With ecosystem loss, exacerbated coastal hazards, and growing coastal populations, increasing damages and costs have been observed (e.g., Bouwer 2019;[207] Hino et al. 2019;[79] Smiley et al. 2022;[208] Al-Attabi et al. 2023[209]), and ongoing health and safety concerns due to increasing flood frequencies, contaminated water supplies, degraded water quality, exposure to toxic substances, and strains on mental health due to the ongoing threat of disasters have been documented (e.g., Coutu 2018;[210] Makwana 2019;[211] Erickson et al. 2019;[212] Gobler 2020;[213] Raker 2022[214]). Additionally, many studies have shown that 1) overburdened, under-resourced, economically disadvantaged, or otherwise vulnerable populations (e.g., children, people with disabilities) face

a greater burden from disasters (e.g., Conzelmann et al. 2022;[215] Raker 2022;[214] Smiley et al. 2022[208]) and are limited in their ability to recover from these impacts, and 2) existing inequities continue to be magnified (e.g., Erman et al. 2020;[216] Griego et al. 2020;[217] Sou et al. 2021;[218] Dundon and Camp 2021;[219] Bento and Elliott 2022[220]). Municipal coastal officials, elected officials, and staff continually document increasing challenges within their communities through participation in professional organizations (e.g., National League of Cities, Association of State Floodplain Managers, regional communities of practice). Specific challenges include the combination of increasing development and land-use pressures and exacerbating coastal hazards that put more homes, businesses, and individuals at risk. Numerous municipalities are installing backflow preventers, documenting high tide flooding, and attempting to manage magnified impacts from rainfall occurring concurrently with high tide flooding and other coastal hazards (e.g., EcoSystems 2014;[221] WSAV 2018;[222] Coutu 2021[223]).

Major Uncertainties and Research Gaps

Future coastal landscape change is difficult to model and predict broadly in the spatially detailed form required by decision-makers, due to the multitude and complexity of the processes and feedbacks acting within and across different coastal ecosystems.[137,224,225]

National-scale efforts are emerging to assess the risk of losing vital coastal wetland habitats[112,226] and to monitor the daily to annual status of sandy beaches using satellite imagery.[227,228,229] However, monitoring alone cannot save these at-risk ecosystems; improved understanding and ability to model the thresholds and/or tipping points associated with ecosystem loss versus survival are needed broadly to support proactive planning for management of coastal resources and communities.[58,137] Information is needed about when and where saltwater intrusion may occur and its impacts.[69,230,231]

Anticipating and accounting for future human modifications that may reshape the coast and/or affect ecosystem behaviors are areas of considerable uncertainty.[232] Multidisciplinary scenario development can help to explore the physical changes that may occur, how humans may choose to respond to these changes, and the resources that may be available to support these modifications, such as emplacement or removal of gray and green infrastructure, planned relocation, or trade-offs.[233,234] A better understanding of when and in what form humans may take future action can in turn help inform understanding of the landscape response, which can better frame the immediate and longer-term risks to coastal populations in the future.[232,235]

Description of Confidence and Likelihood

Based on observations and predictive modeling the authors have *high confidence* that the long-term sustainability of our coastal ecosystems and human systems is *very likely* being affected by climate changes, particularly due to land loss. Observations and modeling have also given us *high confidence* that human measures that have historically been used to limit coastal change and have predominantly relied on hard, fixed infrastructure solutions to protect development are *very likely* to make coastal areas less resilient to future change amplified by climate drivers. With this reduction in resilience, numerous studies have shown there is *high confidence* that coastal ecosystems are *very likely* to be limited in their ability to provide the services on which humans depend. There is *high confidence* based on the array of literature and studies available that the loss of these services are *very likely* to require proactive strategies to address significant and cascading impacts on cities, communities, and ways of life in the coastal zone.

Key Message 9.3

Adaptation Reduces Risk and Provides Additional Benefits for Coastal Communities

Description of Evidence Base

Because coastal hazards will continue to worsen and the impacts to the natural and built environment will increase, coastal communities will have to adapt (or continue to adapt) to climate change. Business-as-usual strategies are not expected to be sufficient in the future because they do not address the root causes of vulnerability in coastal communities[9,14,15] nor acknowledge that sea levels will continue to rise beyond typical infrastructure planning time horizons.[141,236]

Consensus is growing to support nature-based solutions (NBSs) and strategies such as planned relocation as essential components of climate adaptation.[149,153,169,237] There is a growing body of literature that demonstrates that NBSs can successfully provide flood risk protection.[115,160,164,165,237] Multiple studies based on laboratory experiments have demonstrated the capacity of NBSs to attenuate wave energy, currents, and storm surges under a range of controlled conditions.[238,239] Additional studies based on field measurements during extreme coastal events have validated these findings within a range of geographical settings and environmental and extreme weather conditions.[154,156,240] Numerical modeling studies have expanded these findings to low-frequency events and a broader range of extreme conditions.[114,161,162] There is growing evidence on the functionality and performance of NBSs for flood risk reduction. This body of literature supports an increasing number of guidelines and practical guidance for NBS planning, design, and implementation.[149,169] State agencies are beginning to require prioritizing NBSs for coastal adaptation, where possible, in lieu of hardened infrastructure.

Planned relocation continues to be a topic of contentious debate in coastal communities, but there is growing evidence that demonstrates openness by communities to include these strategies in long-term planning discussions.[241] This is particularly true if the definition of planned relocation is broadened to include different land-use policy levers that are common planning tools, such as setbacks or easements,[242] as well as discussions and planning that are led by the community.[243]

Transformative adaptation to SLR is possible, in part, due to the array of efforts used to provide meaningful and understandable information to coastal stakeholders. In the coastal zone, stakeholders span a wide array of sectors, grappling with different priorities, timelines, and urgencies that often lead to differing needs. For example, ecologists designing a wetland restoration require probabilistic estimates of near-term SLR, while planners of critical infrastructure need to understand the full suite of possible risks across both the near term and long term to make wise decisions and investments for the communities they serve. The current state of the science and the corresponding guidance on how to make decisions in the face of the knowns and unknowns around rising seas (e.g., The Application Guide for the 2022 SLR Technical Report) are essential indicators that transformative adaptation, inclusive of NBSs and migration, is achievable.[1]

Major Uncertainties and Research Gaps

Although it is generally understood that riverine flood risk-reduction projects, such as increasing levee heights, could exacerbate flood risks in downstream communities, the potential for a similar deflection of flood risks from one community in coastal environments is less understood. In San Francisco Bay, a modeling study showed that the addition of a levee or seawall to protect one community could increase flood risks elsewhere on the estuarine shoreline.[6] This concept may be important to consider more broadly along the coast, as it intersects with equity considerations if communities with fewer resources to adapt are confronted with increased risks diverted from communities with greater resources.

Despite the growing number of studies investigating and validating the performance of NBSs for flood risk reduction, research gaps remain with respect to uncertainty in flood risk-reduction benefits under a range of future environmental conditions and hazards, given the intrinsic dynamic nature of NBS systems. Specifically, what strategies work in active coastal zones with high wave energy? Furthermore, research is lacking with respect to NBS strategies in extreme environments, especially the Arctic, where traditional vegetation-centric approaches are not practical. This is especially relevant in western Alaska, where communities are experiencing increasing flood hazards and traditional flood protection is extremely costly. While there has been progress on developing standards and guidelines for using NBSs to reduce flood risk,[149,167,168,169] there remains a need for professional engineering organizations and nongovernmental organizations to expand the existing documentation.

Uncertainties and research gaps on planned relocation tend to focus on the process and willingness of communities to relocate: What are the tipping points that encourage a community to adopt community-wide planned relocation? Where should people move to, and are receiving communities prepared to take in increased populations? How does relocation get paid for? How can the psychological barriers to planned relocation be overcome?

There is a lack of literature exploring the governance structures, laws, and policies necessary to support transformative adaptation, including planned relocation. Spanning the gap between adaptation planning and successfully implementing adaptation solutions on the ground requires overcoming governance challenges.[244] Although the number of legal analyses relevant to adaptation is growing, these analyses are still limited in their practical application and scope.[245,246] Research has demonstrated the value of multidirectional policies, laws, and efforts at stimulating climate planning and adaptation, particularly the benefit of top-down laws directing the need to plan and implement adaptation without being overly prescriptive;[53] however, this work is in its early stages. Comprehensive analyses that explore how current policies impede or foster transformative climate adaptation would help to synthesize and identify where improvements could be made within governance structures to support successful adaptation.

There is limited research on the economic and social drivers of, and impediments to, transformative adaptation in coastal communities. Research is also lacking on the social psychology prerequisites needed for successful transformative adaptation. How will a coastal community know when residents are ready to start down the path of transformative adaptation? How can psychological readiness be fostered, including effective communication of future conditions that may compel this sort of action?

Beyond NBSs and planned relocation, many incremental adaptations are well understood in terms of implementation and impact alone. For example, many communities have experience with raising roads, resizing drainage culverts, and building shoreline stabilization structures. However, research that results in effective guidance is lacking for larger measures, such as infrastructure abandonment or relocation and the aggregation of smaller measures. While there is an emerging body of research on this topic for individual actions,[174,247,248] analysis at the community level across a range of adaptation actions and timelines is lacking.

The body of research supporting transformative adaptation is growing; however, much of this research is not tailored for coastal communities. There is a gap in research on the preconditions for, and drivers of, success in coastal communities. Furthermore, there is also a gap in research that assesses the effectiveness of mitigation and adaptation approaches under low-likelihood, high-impact scenarios, given that these approaches necessarily change under extreme SLR scenarios.

Description of Confidence and Likelihood

Increasing coastal hazards, changing weather patterns, and extreme storms are causing widespread and rapid changes along our Nation's coasts (high confidence). At present, adaptation efforts are most often

incremental in nature and sector-specific (e.g., focused on adapting a wastewater treatment plant or stretch of roadway) as opposed to community-wide in scale (high confidence). As SLR accelerates, exposing greater populations and geographies to coastal hazards, this adaptation approach will become ineffective.

Adaptation responses that move beyond traditional solutions may include nature-based solutions and planned relocation. There is medium confidence that nature-based solutions and planned relocation strategies, when they are community-led and equity-centered, can provide an equitable response to coastal hazards and climate change impacts. There is medium confidence that transformative adaptation that centers the community within the planning, design, and implementation of multi-benefit solutions can better maintain the social, cultural, and economic connections communities require to thrive.

The statements in this Key Message are supported both in the literature cited and in the author team's understanding of the state of the adaptation practice across a wide variety of coastal communities, both in geography and in social systems. This community-focused lens supplements the published literature and allows the authors to reflect the most current consensus on this topic.

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Fifth National Climate Assessment: Chapter 10

Ocean Ecosystems and Marine Resources



Chapter 10. Ocean Ecosystems and Marine Resources

Authors and Contributors

Federal Coordinating Lead Author

Emily B. Osborne, NOAA Oceanic and Atmospheric Research, Atlantic Oceanographic and Meteorological Laboratory

Chapter Lead Author

Katherine E. Mills, Gulf of Maine Research Institute

Chapter Authors

Richard J. Bell, The Nature Conservancy

Charles S. Colgan, Middlebury Institute of International Studies at Monterey, Center for the Blue Economy

Sarah R. Cooley, Ocean Conservancy

Miriam C. Goldstein, Center for American Progress (through February 2023)

Roger B. Griffis, NOAA Fisheries

Kirstin Holsman, NOAA Alaska Fisheries Science Center

Michael Jacox, NOAA Southwest Fisheries Science Center and NOAA Physical Sciences Laboratory

Fiorenza Micheli, Stanford University

Review Editor

Andrew A. Rosenberg, University of New Hampshire

Cover Art

Olivia D.

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Introduction

The ocean supports diverse and productive marine ecosystems that provide innumerable benefits to the United States. Fishing, recreation and tourism, energy, shipping, and transportation in the ocean and Great Lakes (see Ch. 24) sustain a marine economy that contributed over $781 billion (in 2022 dollars) to the US economy in 2021.[1] Ocean resources support human health and well-being in communities throughout the US, and sustained connections to the ocean are foundational to cultures and identities. This chapter assesses climate impacts and risks to US marine ecosystems, and to the communities and industries that depend on them, as well as ocean-based measures for climate change adaptation and mitigation.

Across the globe, climate change is altering marine ecosystems and connected social systems at a scale and pace that is unprecedented in recent millennia. The combination of long-term changes in physical ocean conditions—such as warming, sea ice loss, acidification, and deoxygenation (KMs 2.1, 3.3)—and short-term extreme events (KM 2.2) such as marine heatwaves threatens marine ecosystems and human communities (Focus on Compound Events). Numerous marine species, from phytoplankton to whales, are altering their distribution, seasonal activities, and behaviors to align with suitable ocean conditions. These changes ripple through the food web, affecting species interactions, ecosystem functions, and biodiversity, as well as conservation, management, and uses of valuable ocean resources.[2] Climate-driven changes to marine ecosystems significantly affect ocean-dependent livelihoods and, in some communities, threaten food supplies and ways of life.[3]

In affected communities, the magnitude of climate impacts and levels of adaptive capacity vary with marine resource dependence, socioeconomic status, and historical and institutionalized inequities.[4,5,6] Some individuals, communities, and industries are adapting to changes, largely through reactionary responses and, in some cases, through coordinated resilience planning.[7,8,9] However, responses are uneven across communities and sectors, and they remain insufficient to meet mounting challenges and costs.[9,10] Global policy choices regarding greenhouse gas (GHG) mitigation govern the intensity and trajectory of future climate impacts and the diversity and effectiveness of adaptation options. Mitigation and adaptation efforts require explicit accountability in social equity, sustainability goals, and fairness in governance and finance to address entrenched inequities that increase climate change risks and adaptation burdens.[5,11]

This chapter draws on global insights to address climate-related changes and challenges in US marine areas. It largely focuses on continental shelf waters, with some discussion of topics that extend shoreward to intertidal areas, and it complements Chapter 9 (Coastal Effects), which extensively covers the topic of sea level rise. The chapter builds upon the climate-related physical oceanographic changes discussed in Chapters 2 (Climate Trends) and 3 (Earth Systems Processes) to highlight some of the unprecedented ecological changes taking place in US marine waters and their impacts on social, economic, and governance systems. Policy directions, planning efforts, and investment decisions being made now will affect mitigation and adaptation options and timelines and will determine the future of our ocean and social and economic systems that rely on it.

Key Message 10.1

Unprecedented Climate Impacts Threaten Ecosystems and Human Well-Being

Climate change is significantly altering US marine ecosystems at a pace, magnitude, and extent that is unprecedented over millennia (*very high confidence*). Changes in species locations, productivity, and seasonal timing are cascading through ecosystems, threatening critical connections between people and the ocean (*high confidence*), especially for Indigenous Peoples (*very high confidence*). Risks to marine ecosystems and the people connected to them will be greater under higher scenarios (*likely*, *very high confidence*) and will depend on the ability of ecological and social systems to adapt to the pace of climate change (*very high confidence*). Continued climate change, particularly under higher scenarios, is projected to push many systems toward novel conditions and critical tipping points (*very high confidence*), beyond which the risk of significant impacts to marine ecosystems, including collapse, is high, adaptation may be insufficient, and human well-being is threatened (*high confidence*).

Observed Changes

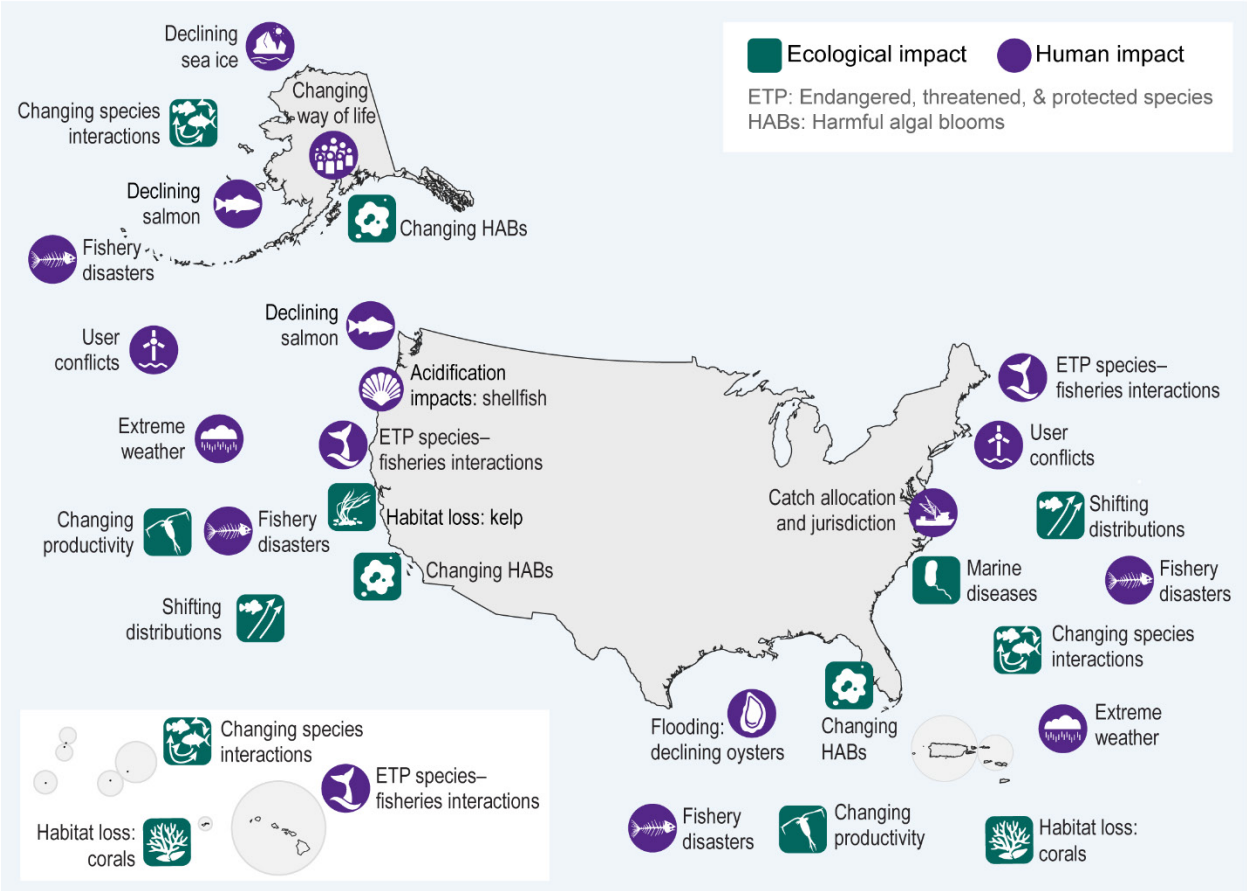
Climate-driven changes are altering marine ecosystems via complex physical, biological, and socioeconomic interactions (Figure 10.1). Many ocean characteristics, such as the timing and length of seasonal cycles, extent and duration of sea ice, oxygen content, and severity of extreme events are exhibiting major divergences from historical patterns (Box 10.1; KMs 2.2, 3.1; Figure A4.11).[10,12,13,14] Changes in distributions, population productivity, and timing of life events are widely documented for marine species and are increasing in prevalence and magnitude (Figure A4.12).[15,16,17,18,19]

Critical habitats such as coral reefs, seagrass beds, and kelp forests have experienced large-scale degradation due to climate-related stressors, threatening their ability to support commercially and ecologically important fish, shellfish, turtles, and marine mammals.[20,21,22,23] Degradation of nursery habitats, spawning areas, and other essential habitats has the potential to affect the productivity and distribution of species.[21,24]

Marine species are shifting their geographic distributions even faster than terrestrial species[25] and are changing the timing of seasonal activities.[16] As changes cascade from microbes to top predators across food webs, these shifts are decoupling some predator–prey relationships[26,27] and amplifying others.[28] For example, shifts in species have reduced prey availability for seabirds, driving large-scale starvation events and breeding-colony failures.[29,30,31]

While warming has benefitted some marine resources in poleward portions of their range (such as an increased abundance of American lobster in the Gulf of Maine[32]), many species—especially those that are cold-adapted, fixed in place, or have complex life histories—have been negatively affected.[33,34,35] Protected and endangered species with limited population resilience, including multiple species of coral, salmon, and whales, are particularly vulnerable to impacts of unfavorable physical and ecosystem conditions (KM 8.2).[22,36,37,38]

Ocean-Related Climate Impacts on People and Ecosystems



Many broad-scale climate-related ecological and human impacts are occurring in US marine areas.

Figure 10.1. Climate change is affecting marine ecosystems and impacting human activities in the US ocean. The nature of ocean-based climate impacts is often unique to local areas but can cascade through social–ecological systems to affect the entire country. For example, extreme weather events impact shipping and supply chains, and harmful algal blooms (HABs) in coastal areas affect tourism. User conflicts, such as those involving the siting of offshore renewable energy in fishing areas, have created tensions in US waters. Climate impacts on physical ocean conditions are covered in Chapters 2 and 3. Figure credit: The Nature Conservancy.

Ocean ecosystems are complex and interconnected, making it challenging to fully understand and anticipate climate-induced changes. Climate impacts are less well documented for certain ecosystem components, even ubiquitous organisms such as microbes[39] and pathogens.[40,41] Additionally, climate drivers impacting ocean ecosystems often act in complex ways and, in some cases, can originate on land. For example, altered precipitation patterns over the continental US have both reduced river flow in the Pacific Northwest and increased flooding on the Mississippi, inducing population declines in iconic species such as Chinook salmon[42] and Gulf of Mexico oysters,[43] respectively. Coastal "blue carbon" ecosystems, including coral reefs, seagrass and seaweed beds, mangrove forests, and tidal marshes, are also impacted by interactions between land- and ocean-based changes,[44,45] and these effects can extend to deep-sea ecosystems (Focus on Blue Carbon).[46,47] While US coastal and shelf ecosystems are relatively well studied, the deep ocean (below 650 feet) remains poorly studied.[48,49] The deep ocean stores and absorbs a vast quantity of carbon and heat, buffering the impacts of climate change but also resulting in warming and changes to biogeochemistry (such as deoxygenation) in this portion of the ocean (KMs 2.1, 3.4),[13,49,50] potentially impairing the health of deep-sea ecosystems and the capacity for carbon sequestration.[51]

Ocean climate impacts affect many communities, from coastal inhabitants who make a living from ocean industries to people who live far from the shore and eat fish in the US Midwest or vacation at Gulf Coast beaches. For example, harmful algal blooms (HABs) and increases in pathogens, such as *Vibrio* species, have become more prevalent in some regions, resulting in beach and fishery closures and impacting people's health and livelihoods.[52,53] Effects are amplified for Indigenous Peoples whose long-standing social, cultural, and spiritual connections to the ocean are being altered.[54,55] Subsistence harvests that are critical for food and nutritional security have been disrupted by shifts in species distributions, sea ice loss that limits access to resources, and HABs that make food sources such as razor clams, Pacific walruses, and bowhead whales unsafe for human consumption (KMs 16.1, 29.5).[56,57,58,59,60,61,62,63] Cumulatively, these changes threaten to break vital social and cultural connections by undermining food security and the mental and physical health and well-being of marine resource users.[59,64,65,66]

As impacts of climate change mount, species and people are beginning to adapt. Examples of observed adaptations include species shifting distributions as they track preferred temperatures[67] and subsistence harvesters changing what, where, and when they harvest.[68] The largest and fastest adaptation responses have followed climate impacts that occur as extreme events (e.g., heatwaves, HABs, hypoxia) or that amplify background risks and pressures (e.g., habitat degradation, resource overexploitation; Box 10.1).[69,70]

Projected Changes

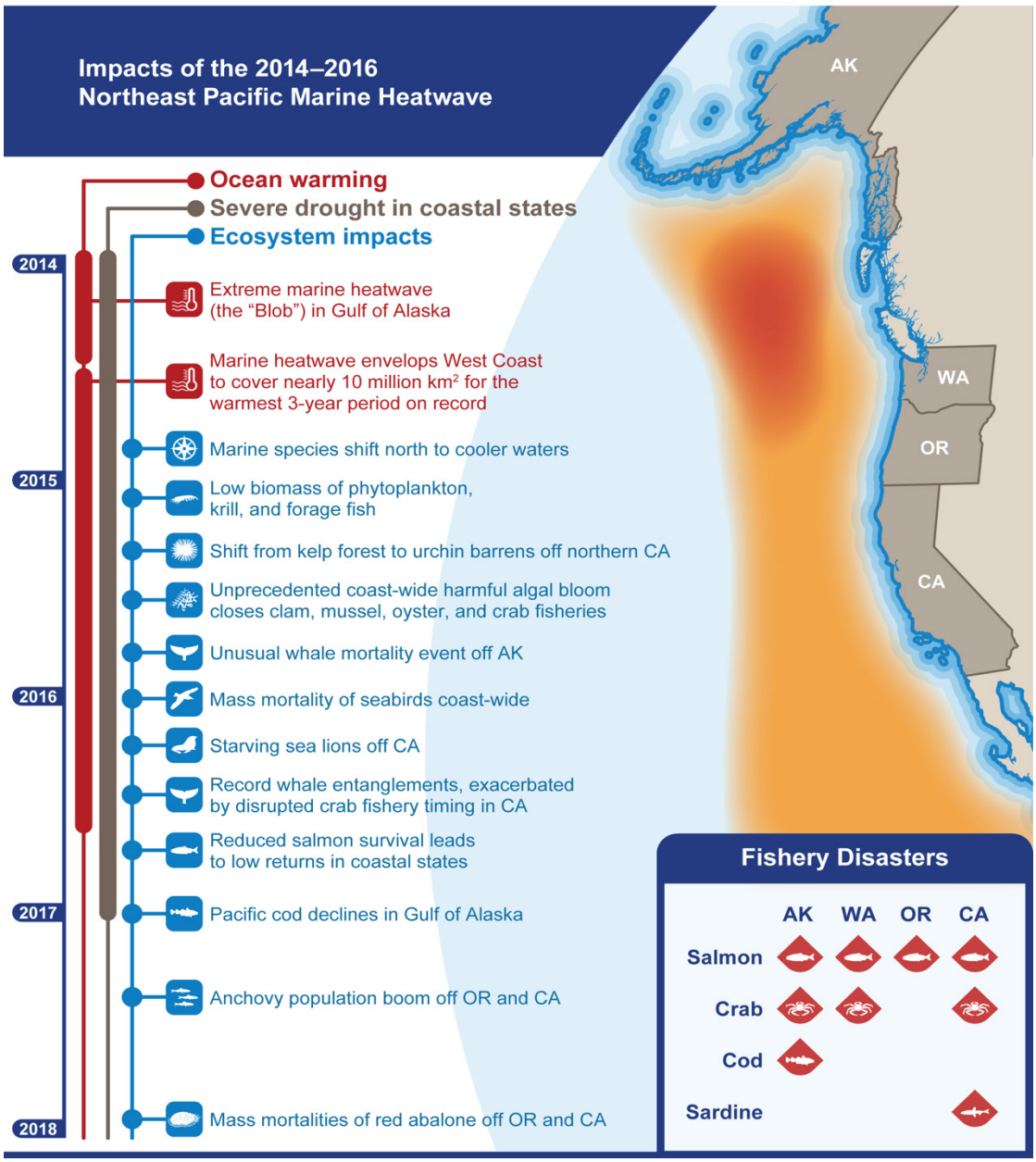
Cumulative GHG emissions will continue to affect marine ecological and social systems over the coming decades. Changes in physical and biogeochemical conditions, including temperature, stratification, upwelling, and ocean chemistry, are projected to become stronger and more widespread, particularly for higher scenarios (KM 2.3),[71] and interactions with chronic stressors such as habitat degradation or overfishing will amplify ecosystem impacts.[10] Shifts in the distribution and biomass of marine species, changes in food web structure and ecosystem functions, and increases in HABs and pathogens will be more pronounced under very high scenarios (RCP8.5, SSP5-8.5).[72,73,74,75] Climate change will drive physical and biological systems toward critical tipping points, triggering feedbacks that may threaten biodiversity, undermine system stability, permanently alter ecosystem functions and services, and limit adaptation options.[76,77,78,79]

Continued climate-driven changes pose challenges for social, economic, and governance systems, particularly those based on expectations that historical conditions will persist into the future. Shifting fish distributions are creating jurisdictional challenges for area-based management, undermining commercial fishery management approaches,[80] and jeopardizing treaty resources such as Tribes' rights to "usual and accustomed" fishing grounds.[81] The severity of impacts to marine social–ecological systems will depend on peoples' ability to adapt at the pace of climate change, which will require participatory governance systems that can effectively and equitably adjust to shifting circumstances.

Box 10.1. Cascading Impacts of a Marine Heatwave

A massive marine heatwave originated in the Gulf of Alaska in the winter of 2013/14 and subsequently encompassed the US West Coast from 2014 to 2016, producing the region's highest three-year average ocean temperature on record.[82] This event, driven by a combination of natural variability and human-caused warming,[82] had widespread impacts on ocean habitat, marine species, and human communities (Figure 10.2). These cascading impacts are illustrated by a chain of events in which, initially, cool-water habitat was compressed along the coast, causing whales to move closer to shore to feed. This shoreward shift resulted in whales foraging in Dungeness crab fishing grounds and becoming entangled in fishing gear.[83] Meanwhile, the warmer ocean and altered ocean chemistry enabled an unprecedented harmful algal bloom.[61,84] Detection of the neurotoxin domoic acid in marine species closed fisheries, delayed opening of the crab fishing season, and led to multiple fishery disaster declarations.[61] Faced with suspension of the fishing season, fishers were forced to forego revenue or shift to other fisheries;[85] adverse impacts were more pronounced for fishers with smaller vessels, who suffered disproportionately large declines in participation and revenue.[86] Finally, when the Dungeness crab fishing season opened late, increased fishing coincided with the migratory arrival of whales, producing another spike in entanglements.[83] Climate shocks like the 2014–2016 marine heatwave amplify environmental and economic impacts that can linger beyond the event itself.[70] Under future ocean warming, heatwaves will become even hotter, with historically rare temperatures occurring more frequently (KM 2.2). The increasingly novel ocean conditions in the California Current system[87] and other regions will lead to more climate surprises that create challenges for planning and decision-making.[88]

Northeast Pacific Marine Heatwave Impacts



The West Coast has experienced unprecedented warm ocean temperatures and environmental disruptions from marine heatwaves.

Figure 10.2. Heatwaves have caused extensive disruptions to marine ecosystems and, in turn, to human communities and economies. Shown here are the widespread impacts of a massive marine heatwave that began in the Gulf of Alaska and subsequently covered the entire West Coast, persisting for several years and coinciding with severe drought over land. Icons on the timeline indicate when impacts occurred; many impacts were sustained for months or years but, for clarity, are shown only at a representative time when they were particularly prevalent. Impacts described as coast-wide or without a specific location occurred off all West Coast states: Alaska, Washington, Oregon, and California. Fishery disasters, as determined by the US secretary of commerce, are shown for individual species (Pacific sardine, Pacific cod) or groups of species (salmon, crab). While the largest heatwave dissipated by 2017, effects of the 2014–2016 heatwave have persisted in the form of lasting ecological changes and new adaptation measures designed to mitigate negative impacts in the future. Figure credit: NOAA Southwest Fisheries Science Center.

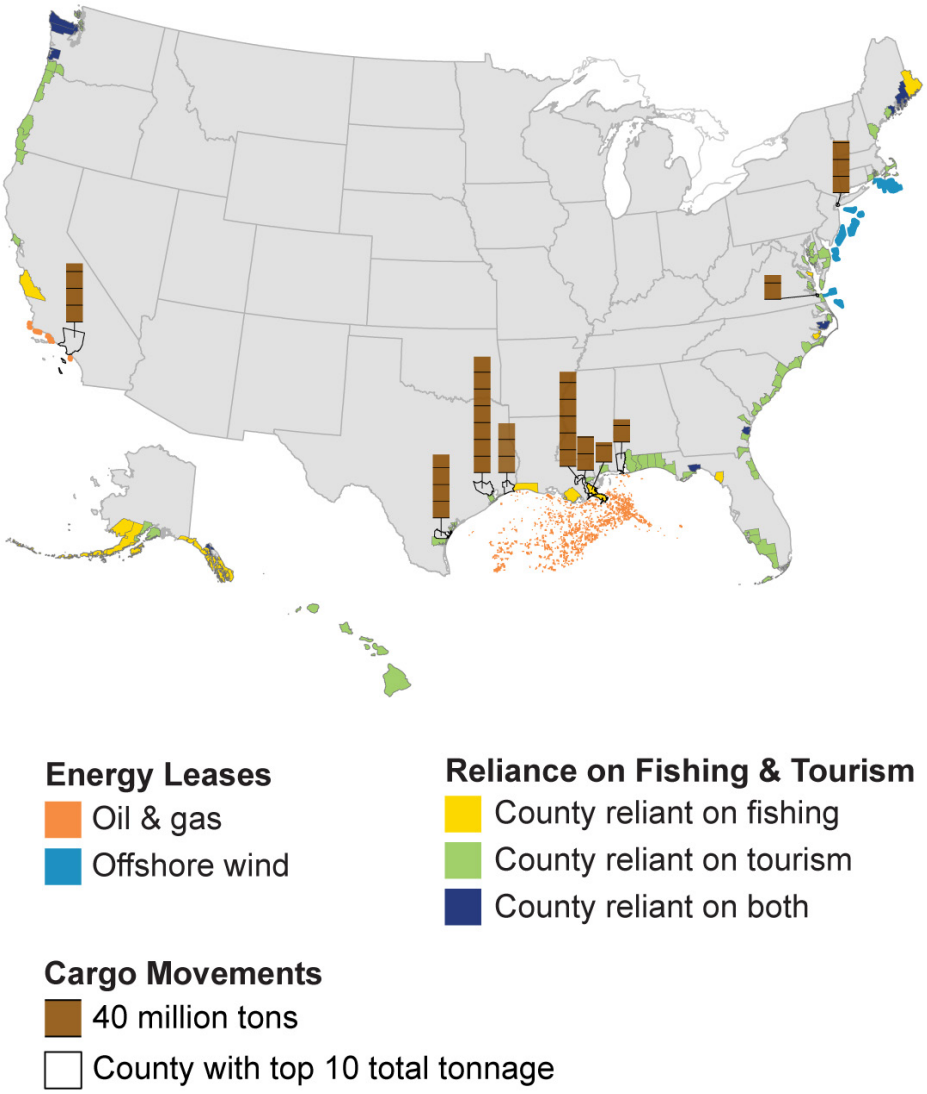
Key Message 10.2

Climate Change Is Altering Marine-Related Economic Activities

Climate change poses a substantial risk to ocean-related industries and economic activities such as fisheries, tourism, recreation, transportation, and energy (*high confidence*). As climate change continues, economic and cultural impacts are expected to become larger and more widespread, especially under higher scenarios and in communities that are highly dependent on ocean resources (*very high confidence*). A range of approaches can facilitate adaptation to some degree of climate change (*medium confidence*), but higher levels of climate change will limit the success of adaptation measures and markedly increase climate risk to marine-related economic activities (*high confidence*).

From energy to fisheries to tourism, the ocean economy is deeply intertwined with the economic health of the United States (Figure 10.3). Populations in shore-adjacent counties grew 5.3% from 2010 to 2019, with employment increasing three times as fast (16.3%). From 2005 to 2019, the ocean-related GDP grew by nearly 60% (in constant dollars), representing a total of 3.5 million jobs.[89] Ocean-based activities and industries are being affected by climate change,[90,91] and future impacts may slow growth of the ocean economy. Limiting global warming to 1.5°C (2.7°F) above preindustrial levels confers clear social and economic advantages compared to higher scenarios.[92,93]

Ocean-Based Economies



Communities throughout coastal America rely on ocean-related industries for major shares of their local economies.

Figure 10.3. Ocean industries such as fishing, shipping, and tourism are important economic activities in coastal communities across the United States. The Nation's continental shelf is a major source of energy from oil and gas, and renewable energy, particularly offshore wind, is being developed in multiple areas. The ocean-based economy is even more critical to the island commonwealths and territories in the Pacific and Caribbean, although economic data comparable to that for the 50 US states are not available. Economic dependence on ocean resources is proportionately highest in rural communities, which have fewer economic alternatives if they experience climate-related disruptions.[94,95] Figure credit: Middlebury Institute of International Studies, NOAA NCEI, and CISESS NC.

Commercial Fisheries

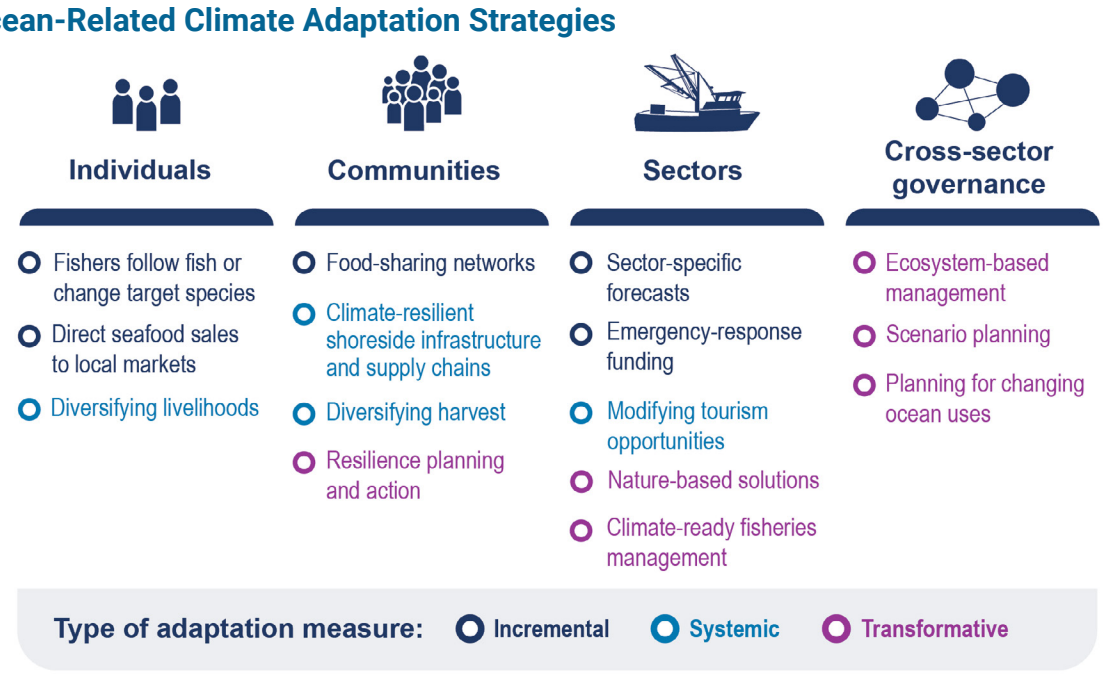
Climate change has impacted commercial marine fisheries in every region of the US by altering the availability and quality of harvested species, destabilizing fisheries-related revenue and employment, and inducing new management challenges.[15,69,85,96,97] The large-scale redistribution of highly valuable Bering Sea (Alaska) Pacific cod and snow crab and subsequent declines in multiple stocks, including closure of the snow crab fishery in 2022, followed low sea ice conditions and protracted warm bottom temperatures across the region (Box 10.1).[98,99,100,101,102] On the East Coast, the northern shrimp fishery collapsed and a fishing

moratorium was imposed following a marine heatwave in 2012,[103] and the highest-valued single-species fishery in the US, American lobster, has seen the southern portion of its population decline to very low levels with warming waters.[32] Disaster declarations for commercial fisheries increased markedly from 1994 to 2019, with more than 84% of fishery disasters linked to extreme environmental events, totaling $3.4 billion of lost revenue and $2.3 billion (in 2022 dollars) in federal funding for disaster relief.[104] Recent climate-related fishery declines have been widespread,[85,105,106] although a few stocks have increased with ocean warming and heatwaves (e.g., regional increases in the northern stock of American lobster, market squid, and sablefish[32,107,108]). While climate is not the sole driver impacting fish populations, it is an added stressor that exacerbates other negative impacts.[33]

Over the next century, climate change is expected to reduce catch in all US regions,[92] including some of the highest-valued fisheries (e.g., Bering Sea snow crab, walleye pollock, Pacific cod, American lobster, and Atlantic sea scallops[32,109,110,111,112]). For 16 species that represent more than half of commercial fisheries revenue, climate-induced changes are projected to result in billions of dollars of economic losses by 2100, with losses twice as high under a very high scenario (RCP8.5) than an intermediate scenario (RCP4.5).[113] Many species will continue moving northward and deeper, reducing accessibility for subsistence harvesters and smaller vessels and complicating management policies and quota allocations.[114,115,116,117,118] Severe storms and sea level rise will increasingly threaten shoreside infrastructure and transportation networks that are critical for harvesting and distributing seafood products (KM 9.1).[4,119]

Climate impacts are not distributed equally across all fisheries and can be compounded by non-climate factors, including fisheries management, market conditions, socioeconomic conditions, and external shocks (e.g., COVID-19).[4,86,115,120] Impacts are generally greater for small-scale coastal harvesters who are less able to follow shifts in fish distribution or who have access to a limited number of fish stocks, while those with larger vessels and more diverse harvest portfolios are generally more resilient.[85,86,118,121] Commercial fisheries and subsistence harvesters are adapting to these changes through short-term incremental measures, business investments appropriate for changing conditions, and management efforts supporting climate-ready fisheries (Figure 10.4).[96,122,123]

The effectiveness of future adaptation responses may be limited by the magnitude of change and factors like inequities in finance and governance across communities, costs of equipment or infrastructure, and access to fishing permits (Focus on Risks to Supply Chains).[80,97,115,124] As fisheries adapt, community initiatives such as permit banks and seafood cooperatives that plan for climate change can enhance equitable opportunities and socioeconomic benefits (Figure 10.4).[125,126] Diversifying harvest and livelihoods, including expanding into marine aquaculture (KM 11.1), can also help stabilize income or buffer risk. Tools that predict species distribution changes can help avoid bycatch, reduce costs, and increase yield.[127] Further, ecosystem-based and climate-informed management can align harvest limits with population productivity to maintain sustainable fishing levels.[109,110,128]



Adaptation can occur at many organizational scales—from individuals to governance systems.

Figure 10.4. Many types of adaptation measures are being undertaken, or are under consideration, as ways to respond to and prepare for climate change impacts on ocean activities and economic sectors. The measures range from small adjustments (incremental) to larger actions within current socioeconomic and management systems (systemic) and substantial changes beyond existing systems (transformative). Figure credit: Gulf of Maine Research Institute.

Tourism and Recreation

Ocean-based tourism and recreation—the largest sector in the ocean economy, representing $274.5 billion of economic activity in 2021 (in 2022 dollars)[1]—is both positively and negatively impacted by climate change.[129] Warming temperatures extend the coastal tourism season, yet sea level rise threatens shoreside facilities (KM 9.2) and will change nearshore wave dynamics in ways that reduce or eliminate some surfing opportunities.[130] In the Gulf of Mexico and Caribbean, worsening HABs[131] and blooms of macroalgae (e.g., *Sargassum*[132]) due to climate and local non-climate stressors have raised human health concerns (KM 23.1) that have disrupted tourism and fishing.[133,134] Recreational fisheries are experiencing climate-related changes in anglers' participation, location choices, and expenditures.[135] As warming continues, angler participation may decline by up to 15%, with losses as high as $413 million annually (in 2022 dollars) along the Atlantic and Gulf of Mexico Coasts; however, warming is increasing participation in some areas (e.g., New England).[136]

Similarly, tourism impacts are different across regions. Arctic sea ice loss is creating tourism opportunities by allowing "last-chance" cruise ship tourists to see ecosystems before they are further altered by climate change.[137] However, coral reef tourism—valued at nearly $3 billion annually for 2008–2012 (in 2022 dollars) in Hawai'i and Florida—is threatened by bleaching and disease that deter divers and snorkelers (KMs 23.3, 30.4).[138] At a more localized scale, the loss of endangered southern resident orca whales in Washington's Puget Sound due to climate-driven declines in food would result in annual losses of $39 million in economic activity (in 2022 dollars).[36,139]

Transportation

Climate change is already affecting marine transportation. Sea ice loss and longer open-water seasons have enabled transit between the Atlantic and Pacific via the Arctic, with ship traffic in the Arctic increasing threefold between 1990 and 2015,[140,141] and Arctic-routed shipping continues to be considered.[142] With 3.6°F (2°C) of warming above preindustrial levels, ships are projected to be able to reliably navigate the Northwest Passage and Arctic Bridge trade routes in summer.[143] These routes may reduce carbon emissions and shipping costs, but concerns exist about impacts to marine species and local communities, as well as about black carbon emissions.[54,144,145,146]

Commercial vessel emissions have increased over time, as has the sector's proportional contribution to global emissions (KM 13.1),[147] but emissions from recreational boats in the US declined between 1990 to 2021.[148] The shipping sector is initiating further measures to reduce its GHG emissions by powering docked vessels with electricity,[149] increasing vessel efficiency to reduce global shipping emissions by 50% by 2050,[147] and planning for some zero-emissions maritime routes by 2025.[150]

Energy

Ocean-based energy production in the US is in a period of transition. Ocean-based energy has been almost exclusively derived from hydrocarbon extraction, which generated $96.4 billion in 2021 (in 2022 dollars).[1] Globally, nearly 30% of commercially recoverable oil and gas assets are found in areas at high risk for climate impacts.[151] In the US, stronger hurricanes, increasing wave heights, and sea level rise will threaten offshore facilities and associated coastal structures, such as underwater pipelines and refineries (KM 9.2).[152,153] Facilities may increasingly require adaptive responses, such as raising the height of oil and gas platforms in the Gulf of Mexico to reduce hurricane damage.[154,155]

Renewable energy sources are expected to increase as part of the ocean-based energy mix over the next several decades. The first US facilities to generate electricity from ocean wind are in place off the Atlantic Coast, and in 2021, the US set a goal of installing more than 30 gigawatts of capacity by 2030, enough to power about 10 million homes.[156] States have set additional goals for offshore wind energy development that may further advance this capacity. Through 2022, more than two million acres of ocean bottom have been leased for wind energy, with more leases anticipated by 2025.[157] The growth of ocean-based renewable energy is expected to bring jobs and economic benefits to certain coastal communities, but its ecosystem impacts are still being determined, and its development may constrain other ocean uses, including fishing, transportation, and aesthetic preferences.[158,159,160,161,162]