Fifth National Climate Assessment

U.S. Global Change Research Program

Full report available online at: nca2023.globalchange.gov

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.

Full report available online at: nca2023.globalchange.gov

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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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Ellen Anderson

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.

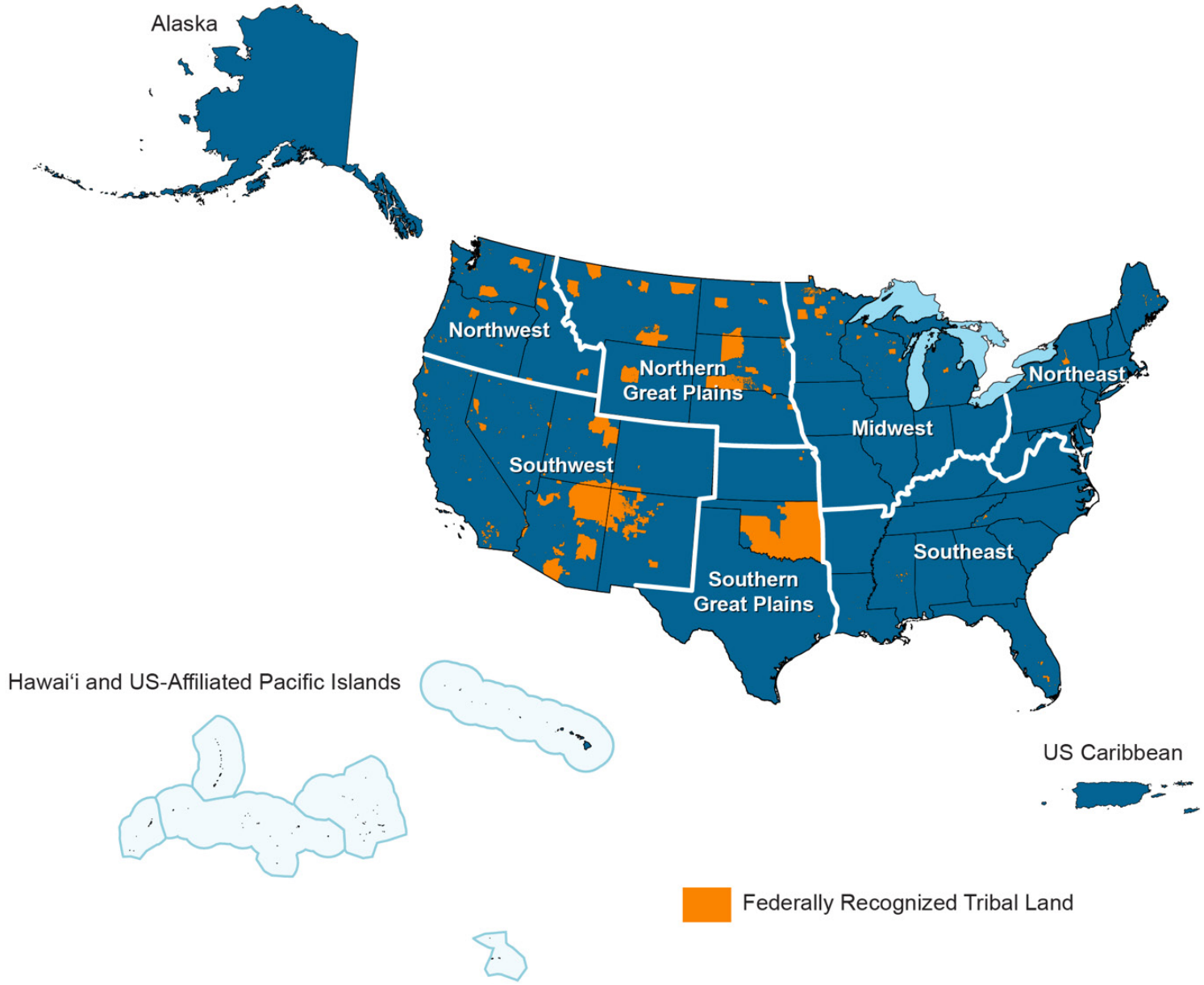
National Topic Chapters

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)

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