



Key Message 1

Cameron, Montana

Water

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

Key Message 2

Agriculture

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

Key Message 3

Recreation and Tourism

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

Key Message 4

Energy

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

Key Message 5

Indigenous Peoples

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

Executive Summary



In the Northern Great Plains, the timing and quantity of both precipitation and runoff have important consequences for water supplies,

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

The Northern Great Plains region plays a critical role in national food security. Among other anticipated changes, projected warmer and generally wetter conditions with elevated atmospheric carbon dioxide concentrations are expected to increase the abundance and competitive ability of weeds and invasive species,^{1,2} increase livestock production and efficiency of production,³ and result in longer growing seasons at mid- and high latitudes.^{4,5} Net primary productivity, including crop yields⁶ and forage production,^{7,8} is also likely to increase, although an increasing number of extreme temperature events during critical pollination and grain fill periods is likely to reduce crop yields.⁹

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures. Higher temperatures, reduced snow cover, and more variable precipitation will make it increasingly challenging

to manage the region's valuable wetlands, rivers, and snow-dependent ecosystems. In the mountains of western Wyoming and western Montana, the fraction of total water in precipitation that falls as snow is expected to decline by 25% to 40% by 2100 under a higher scenario (RCP8.5),¹⁰ which would negatively affect the region's winter recreation industry.¹¹ At lower-elevation areas of the Northern Great Plains, climate-induced land-use changes in agriculture can have cascading effects on closely entwined natural ecosystems, such as wetlands,¹² and the diverse species and recreational opportunities they support.

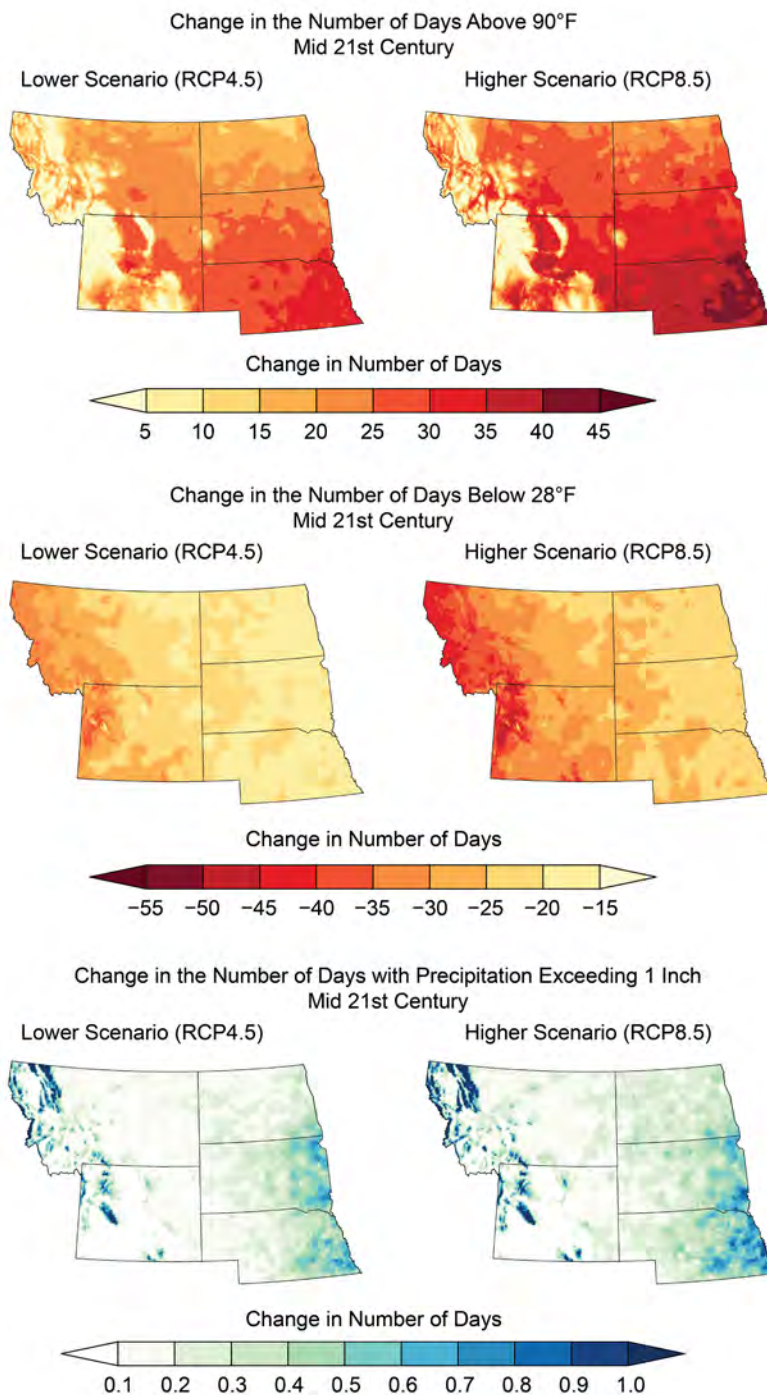
Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, and stored water, and to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change. Railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion.¹³ Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources.¹³ These cost increases will either lead to lower production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.¹³

Indigenous peoples in the region are observing changes to climate, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies, medicines, and health and well-being.^{14,15,16,17,18,19,20,21,22,23,24,25,26} Because some tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still

directly reliant on natural resources, they are among the most at risk to climate change (e.g., Gamble et al. 2016, Cozzetto et al. 2013, Espey

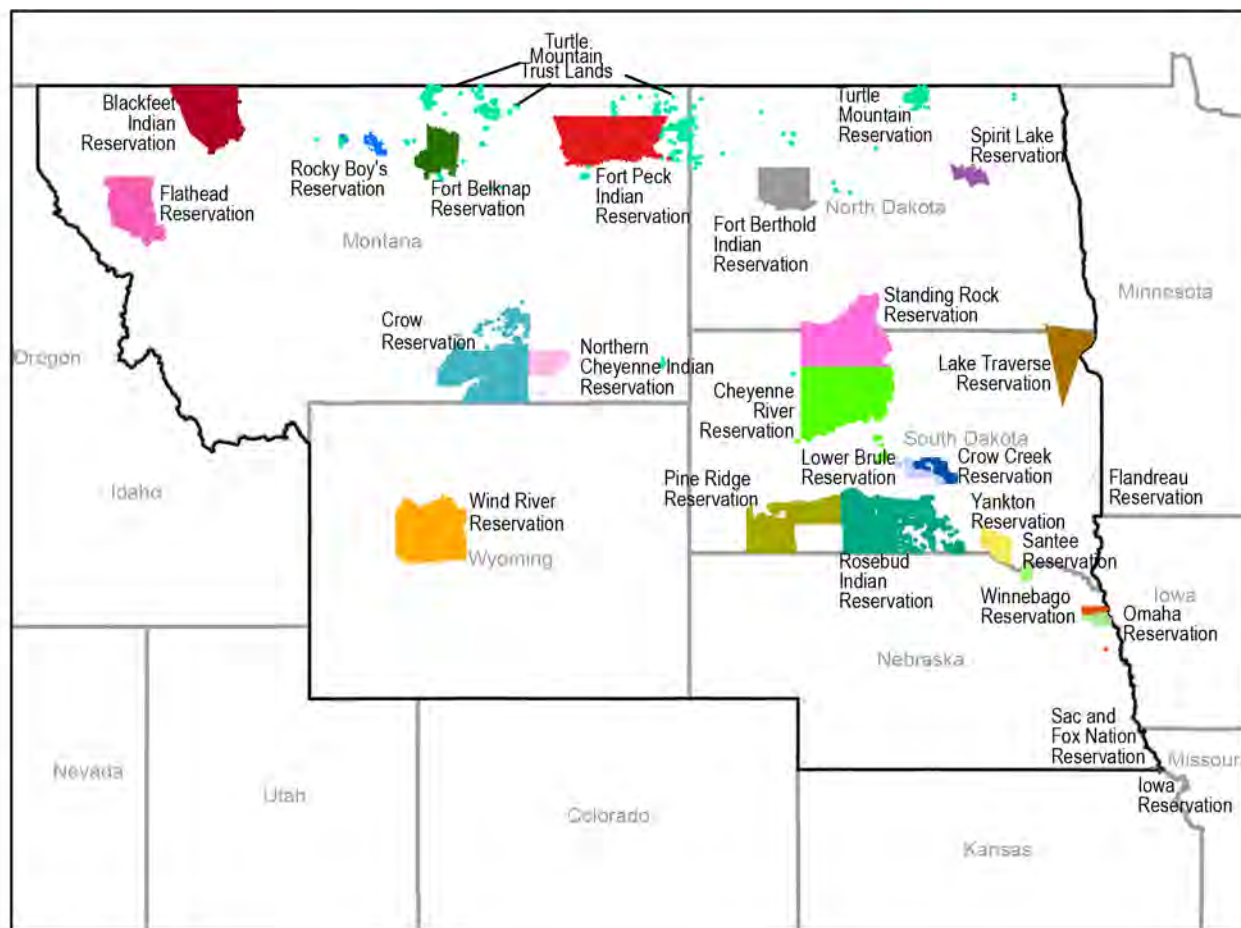
et al. 2014, Wong et al. 2014, Kornfeld 2016, Paul and Caplins 2016, Maynard 2014, USGCRP 2017^{18,24,25,27,28,29,30,31}).

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



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

Northern Great Plains Tribal Lands



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

Background

The Northern Great Plains has three distinct regional geographic features associated with a strong east-to-west gradient of decreasing precipitation and a stark rise in elevation at the montane western boundary. The eastern edge of the region includes a humid-continental climate and the Red River Valley, where the capacity to store water is often exceeded, leading to extensive flooding. A large swath of the central Northern Great Plains falls within the Upper Missouri River Basin. Much of this basin is arid to semiarid, and because temperatures and rates of evapotranspiration (the evaporation of water from the soil and transpiration from plants) are so high, only 9% of precipitation ultimately reaches the Missouri River as runoff. For comparison, other basins in the United States yield more than 40% runoff. In the mountainous far western part of the region, including central and western Wyoming and Montana, water dynamics are driven by large seasonal snowpack that accumulates in winter and early spring and provides critical resources for non-montane areas through runoff during the warm season.

These intraregional gradients in precipitation, temperature, and water availability drive east-west differences in land use and climate. The eastern portion of the region is characterized by rainfed row crop agriculture and is often subject to flooding. For example, Devils Lake in North Dakota is a closed basin, meaning that it has no natural outflows. The basin is often so full that it is prone to flooding the communities around it. Separately, the irrigated cropland and grazing lands in the central portion of the Northern Great Plains are critical for U.S. livestock production, yet the arid to semiarid climate is highly variable from year to year, which makes it difficult to manage agriculture, recreation, and cultural resources. The western portion of the region is devoted

primarily to native ecosystems used for grazing and recreation, but dryland cropping is also important, and forestry is important in the far-western edge of the region. Coal, oil, and natural gas are produced throughout the Northern Great Plains.

The highly variable climate of the Northern Great Plains poses challenges for the sustainable use of water, land, and energy resources by competing urban, suburban, rural, and tribal populations. Climate change is expected to exacerbate those challenges, which include 1) effectively managing both overabundant and scarce water resources, 2) supporting adaptation of sustainable agricultural systems, 3) fostering conservation of ecosystems and cultural and recreational amenities, 4) minimizing risk to energy infrastructure that is vulnerable to climate change and extreme weather events, and 5) mitigating climate impacts to vulnerable populations.

Diverse land uses across the region are overlain with a quilt work of private, state, federal, tribal, and other land ownership. Many of these institutions foster adaptation to existing climatic variability (Figure 22.1). For example, the Missouri Headwaters Drought Resilience Demonstration Project was launched in July 2014 to demonstrate how federal, state, and local stakeholders can work together to build long-term drought resilience. The project leverages federal and state resources and engages communities in the development and implementation of local watershed drought resilience plans and activities. Led by the Montana Department of Natural Resources and Conservation, more than 10 federal agencies, 20 watershed groups, and 14 nongovernmental organizations are contributing to the project (see Missouri Headwaters Drought Resilience Demonstration Project 2015³²). It is a replicable model that is producing concrete, on-the-ground results, including tools for drought monitoring, assessment, and forecasting. In another example,

Climate Change Impacts and Adaptation Across the Northern Great Plains

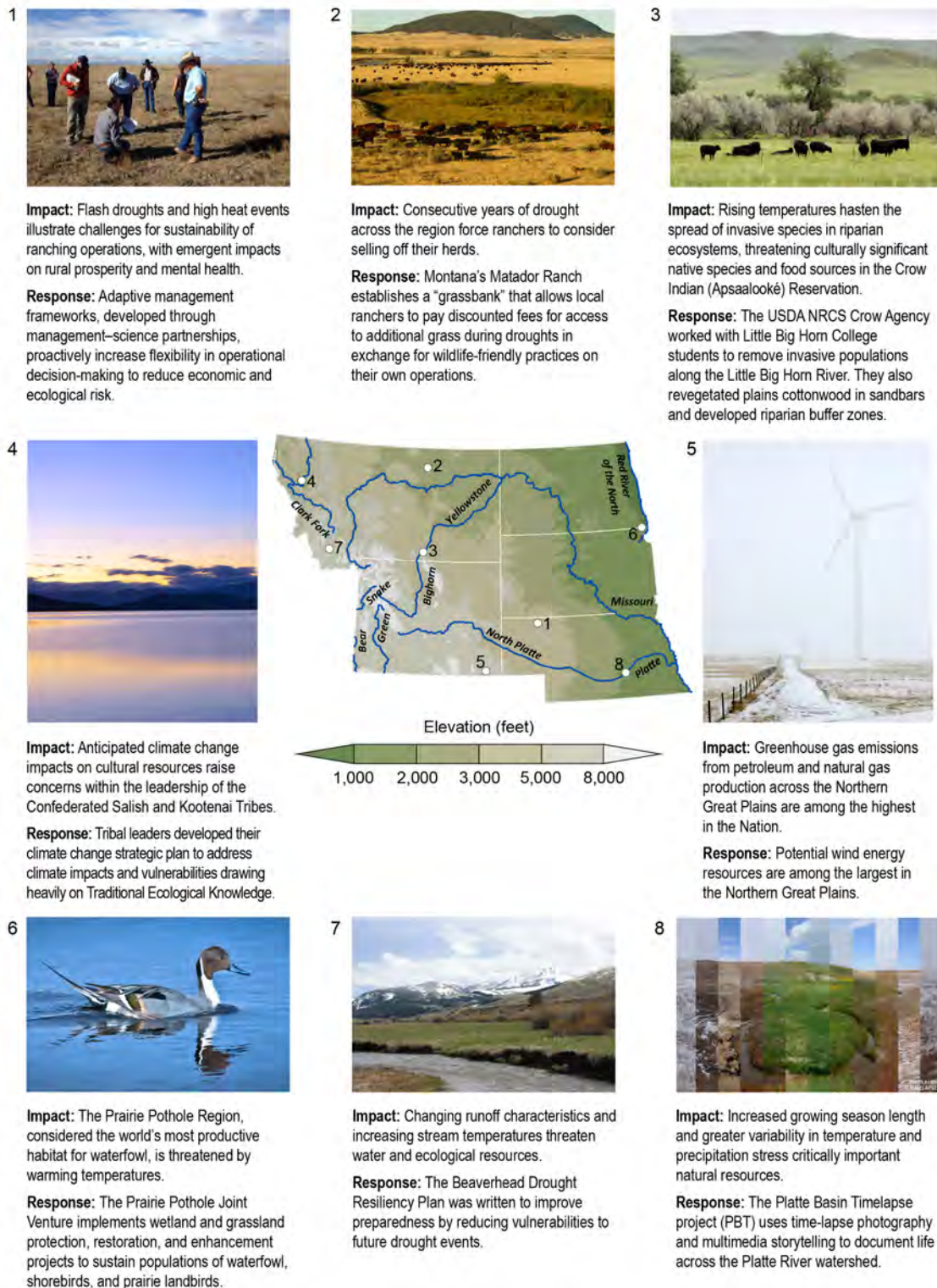


Figure 22.1: The Northern Great Plains exhibits a high amount of geographical, ecological, and climatological variability, in part because of the dramatic elevation change across the region. The impacts of climate change throughout the Northern Great Plains include changes in flooding and drought, rising temperatures, and the spread of invasive species. Ranchers, tribal communities, universities, government institutions, and other stakeholders from across the region have taken action to confront these challenges. Photo credits: 1) Justin Derner, USDA Agricultural Research Service, 2) Kenton Rowe Photography, 3) Kurrie Jo Small, 4) Eugene Wilson (CC BY-NC 2.0), 5) Jacob Byk, 6) Benjamin Rashford, 7) Chris Carparelli, 8) Mariah Lundgren, University of Nebraska Platte Basin Timelapse Project.

Nebraska completed a statewide climate change assessment report in 2014.³³ Officials were then able to use this report to convene eight sector-based roundtable discussions in 2015, engaging more than 350 people, to identify a suite of key issues, strategies, and next steps to help develop a statewide climate change action plan.³⁴

Key Message 1

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

Streamflow in the Northern Great Plains is driven by a number of factors. Because the Northern Great Plains is so far from the coasts and the modulating effect of the oceans, the regional climate system is prone to dramatic climate variability. The Upper Missouri River Basin (the region's primary surface water feature spanning all five states) is very sensitive to climatic fluctuations, resulting in extreme drought or flooding events roughly every decade over the past century.³⁵ The timing and quantity of both precipitation and runoff have important consequences for water supplies, agricultural activities, and energy production. Parts of the region are among the most arid in the Nation—for example, less than 10% of regional precipitation reaches streams and the Missouri River³⁶—so relatively small changes in annual precipitation can produce large changes

in runoff. High evaporation rates result in lower soil moisture and streamflow in the region relative to more humid parts of the country. Trends in annual runoff across the region over the past 50 years show a distinct east–west difference where the western portions show a decrease and eastern areas show an increase.³⁷ Soil moisture and snowpack have a major impact on streamflow, and as a result of these factors combined with variability in precipitation, the amount of annual streamflow can vary by as much as a factor of three from year to year.³⁵ In the western montane portion of the region, 39 glaciers contribute to streamflows through their seasonal melt process. These glaciers are experiencing sustained loss,³⁸ and, like global glacier losses over recent decades, local glacier losses are attributable to higher temperatures.^{39,40} Glacier flows are critically important for local watersheds and ecosystems; however, their contribution to the entire Upper Missouri River Basin is very small. High variability in the proportion of precipitation that reaches streams in a given year, coupled with a relatively high frequency of extreme events (for example, heavy rainfall events and droughts), makes managing climate change impacts on water resources challenging. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

Given the losses in important snowpack water storage, reservoirs and groundwater represent critical buffers to climate impacts, since they have large storage capacity that can be filled during wet periods and withdrawn during dry periods. Evaporation rates exceed 100% of precipitation in some cases,⁴¹ which results in a deficit of surface water and thus reliance upon groundwater. Groundwater and aquifer recharge rates⁴² are relatively high in the region (including parts of Wyoming, South Dakota, Montana, and Nebraska) and seem sustainable given current rates of groundwater extraction.

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

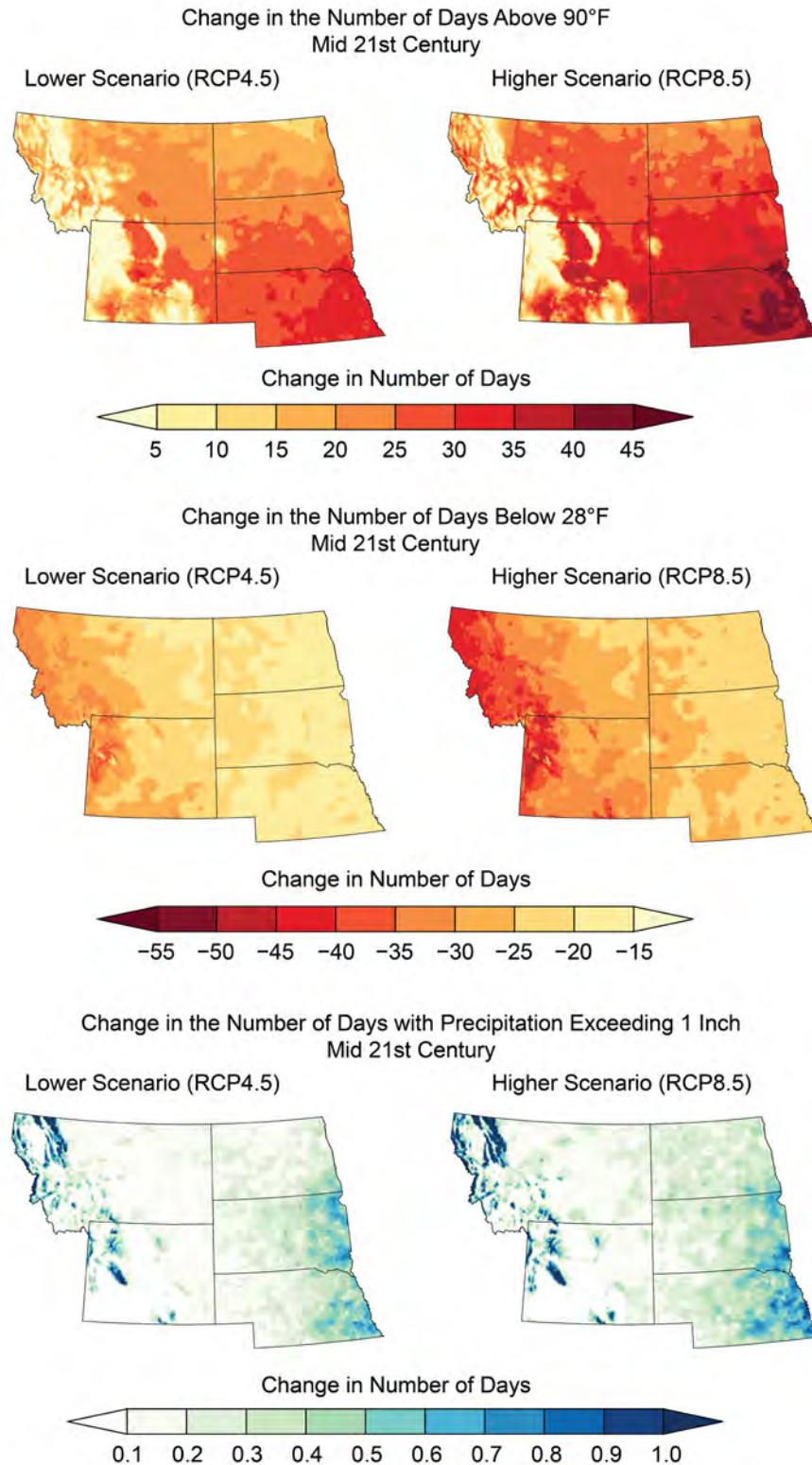


Figure 22.2: Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost),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

Hydrologic Changes Across the Northern Great Plains

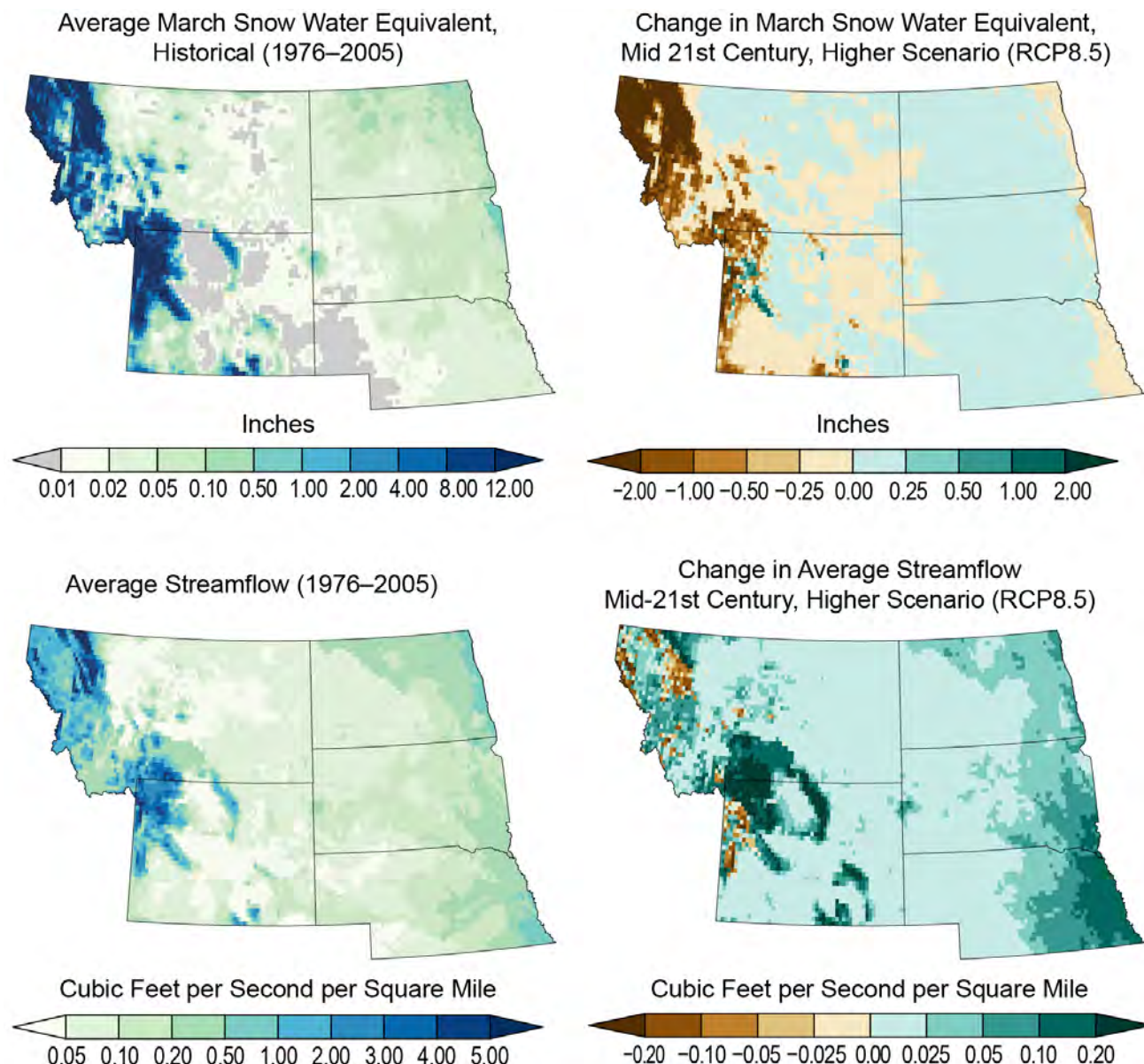


Figure 22.3 These maps show historical (left; 1976–2005) and projected changes (right; 2036–2065) under a higher scenario (RCP8.5) in average snowpack (top row) and annual streamflow (bottom row). Snowpack is measured in terms of snow water equivalent, or SWE—the depth in inches of the amount of water contained in the snowpack. The top two maps show average values for March to provide historical and future end-of-season estimates of SWE. This illustrates projected warming and potential snow loss. Projected decreases in snowpack across montane western regions in the upper-right plot are primarily the result of projected warming at the highest elevations. Projected increases in snow at lower elevations are less important, since those changes are relative to a much lower average (top left) than in montane regions. Similarly, annual streamflows are expected to increase across much of the eastern part of the region, with isolated but important decreases in the western highlands. In this context, streamflow refers to the sum of surface runoff and subsurface flow for each location in space. Sources: NOAA NCEI and CICS-NC.

Climate model projections paint a clear picture of a warmer future in the Northern Great Plains, with conditions becoming consistently warmer in two to three decades and temperatures rising steadily towards the middle of the century, irrespective of the scenario selected

(Figure 22.2). This warming is projected to occur in conjunction with less snowpack and a mix of increases and reductions in the average annual water availability (Figure 22.3). Precipitation and streamflow projections show only modest changes, but many areas within

the region are already subject to a high degree of year-to-year variability—both wet and dry years. Low-probability, but high-severity and high-impact, events are the result of large variability, including both extreme flood events like in 2011 and drought events like in 2012. This interannual variability implies greater uncertainty about future climate and about the potential for future flooding and drought.

An important takeaway is that the magnitude of variability overshadows the small projected decrease in average streamflow.³⁵ Changes in extreme events are likely to overwhelm average changes in both the eastern and western regions of the Northern Great Plains (Figure 22.2). Overall, climate models project an increase in the number of heavy precipitation events (events with greater than 1 inch per day) for much of the region, with the exception of the high-mountain areas in the southwestern portion. Societal risk increases any time natural conditions differ greatly from historical conditions,⁴³ with larger changes representing greater risks. Therefore, any large projected changes will require rethinking infrastructure design and operation. The probability for more very hot days (days with maximum temperatures above 90°F; Figure 22.2) is expected to increase, with potential impacts on agriculture, energy production, human health, streamflows, snowmelt, and fires. There are projected to be many fewer cool days (days with minimum temperatures less than 28°F, an indicator of damaging frost; Figure 22.2), with decreases of 30 days or more per year by mid-century. These changes would have important implications for the region's snowpack and consequently streamflow and water use.

Reservoir and groundwater storage are expected to be increasingly important as buffers against the impacts of increasing variability and to meet water demands during periods of shortage, especially in light of

warming-driven losses in snowpack water and higher evapotranspiration rates, which reduce the total amount of water availability. It may be possible to move water between basins to alleviate flooding impacts, but this raises a new set of challenging hydrological and environmental issues. Future activities that increase water demand (population growth, expansion, or alteration of agriculture) will increase dependence on reservoir capacity and infrastructure integrity.

Key Message 2

Agriculture

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

The Northern Great Plains region plays an important role in U.S. food security (see Tables 22.1 and 22.2), and agriculture has been integral to the history and development of the region. Agricultural uses in the region are diverse, including the largest remaining tracts of native rangeland in North America, substantial areas of both dryland and irrigated cropland and pasture, and mosaics of cropland and grazed

grassland and forested lands. This region is home to 7.2% of U.S. farms (152,663) but 23.8% of the U.S. land in farms, encompassing 218 million acres with 22.4% of the total cropland, 21.9% of irrigated lands, 29.3% of U.S. pasture and rangeland, and nearly one-third (30.1%) of lands in conservation/wetland reserve programs.⁴⁴ Livestock production (beef and dairy cattle and hogs) is dominant in the region. Important crops include corn, soybeans, wheat, barley, alfalfa, hay, and a diversity of other crops such as potatoes, sugar beets, dry beans, sunflowers, millet, canola, and barley (see Tables 22.1 and 22.2).⁴⁴ The Northern Great Plains region contributes 12.7% of the market value of agricultural products sold in the United States despite having only 1.5% of the U.S. population.

Extensive precipitation and temperature gradients and inherently high climatic variability, both within and between years, result in highly variable conditions for agricultural enterprises in the Northern Great Plains. The region receives the majority of its precipitation during the spring months (April, May, and June), with a high degree of year-to-year variability.⁴⁵ A mix of private, state, federal, tribal, and other land ownership across the region promotes heterogeneity at landscape-to-regional scales, which enhances the provision of numerous ecosystem goods and services, such as wildlife habitat, including for pollinators.

Percent of National Total Livestock Animals in the Northern Great Plains (2012)

	Beef cows	Hogs and pigs	Sheep and lambs	Milk cows	Egg layers
% of National Total	21.9%	6.9%	18.4%	2.0%	3.5%

Table 22.1: The table shows the percent of the national total of livestock animals living in the Northern Great Plains in 2012. Source: U.S. Agricultural Census 2012.⁴⁴

Percent of National Total Crop Commodities in 2012

	Corn for grain (bu)	Corn for silage/ greenchop (tons)	Wheat for grain (bu)	Spring wheat (bu)	Durum wheat (bu)	Oats for grain (bu)
% of National Total	20.2%	11.5%	30.4%	70.6%	72.2%	20.3%

	Barley (bu)	Soybeans (bu)	Dry edible beans and lentils (cwt)	Forage (tons)	Sunflower seed (pounds)	Sugarbeets (tons)
% of National Total	48.4%	16.3%	48.6%	13.8%	83.6%	27.2%

Table 22.2: The table shows the percent of the national total production for crop commodities produced in the Northern Great Plains in 2012. Units are bushels (bu), tons, hundredweight (cwt), or pounds. Source: USDA National Agricultural Statistical Survey 2012.⁴⁴

The Northern Great Plains is currently experiencing a marked transition in agricultural land use involving the conversion of grassland to annual crops^{46,47} and an increased prevalence of monoculture cropping.⁴⁸ From peak enrollment in the Conservation Reserve Program (10 million acres in 2007), enrollment declined by half by 2017, with the majority of these lands returning to cropland (60%), thereby losing ecosystem service benefits such as wildlife habitat and improved water and soil quality.⁴⁹ Changing land use in the eastern part of this region is an outcome of trends of above-average precipitation over the last 10–20 years, with some of those precipitation trends having been driven by expansion of agricultural land use.⁵⁰ In the western part of the region, genetic developments in crop cultivars and varieties that enhance suitability of drier land for crop production have led to expansion of dryland cropping.

Despite a long history of high year-to-year variability,⁴⁵ producers are experiencing a changing climate and increasing weather variability and extreme conditions that are outside the ranges they have dealt with in the past.⁵¹ Producers' daily and annual decision-making depends on market conditions for seeds and products, agronomic constraints, and climate change-related variables.⁵² The decision-making process is challenged by a lack of experience with analogous climatic conditions in the past, thus increasing risks for land managers. This dependence on historical experience highlights the importance of the human element in the resilience of social-ecological systems, which have traditionally been viewed from the biophysical perspective.⁵³

Temperature increases of 2°–4°F projected by 2050 for the Northern Great Plains under the lower scenario (RCP4.5) are expected to result in an increase in the occurrence of both drought and heat waves; these projected trends would be greater under the higher scenario (RCP8.5). The amount, distribution, and variability of annual precipitation in the Northern Great Plains are anticipated to change, with increases in winter and spring precipitation of 10%–30% by the end of this century and a decrease in the amount of precipitation falling as snow under a higher scenario (RCP8.5).⁵⁴ Summer precipitation is expected to vary across the Northern Great Plains, ranging from no change under a lower scenario (RCP4.5) to 10%–20% reductions under a higher scenario (RCP8.5).⁵⁴ Further, the frequency of heavy precipitation events is projected to increase, with an increase of about 50% in the frequency of two-day heavy rainfall events by 2050 under the higher scenario (RCP8.5). The amount falling in single-day heavy events is projected to increase 8%–10% by mid-century depending on scenario.⁵⁴ Although fewer hail days are expected, a 40% increase in damage potential from hail due to more frequent occurrence of larger hail is predicted for the spring months by mid-century under a higher scenario (RCP8.5).⁵⁵ Even with increases in precipitation, warmer temperatures are expected to increase evaporative demand, leading to more frequent and severe droughts.⁵⁶ Some of the negative effects of drying in a warmer climate are likely to be offset by elevated atmospheric carbon dioxide (CO₂) concentrations, which directly stimulate plant growth and increase plant water-use efficiency.³

The warmer and generally wetter conditions projected for some of the Northern Great Plains, coupled with elevated atmospheric CO₂ concentrations, are expected to

1. increase soil water availability during the primary growing season in the northern part of the region and decrease it the southern parts;^{1,9}
2. increase the number of extreme temperature events (high daytime highs or nighttime lows) during critical pollination and grain fill periods, which will very likely reduce crop yields;^{6,9}
3. lead to declining yield for crops⁶ and forages^{7,8} due to increasing temperatures, some of which will be offset by increasing CO₂;
4. increase the abundance and competitive ability of weeds and invasive species;^{1,2}
5. alter plant phenology—for example, earlier onset of spring (Ch. 1: Overview, Figure 1.2j)⁵⁷ and earlier flowering of plants;⁵⁸
6. decrease the quality of forage available to livestock;^{3,59,60}
7. increase livestock production and efficiency of production due to greater net primary productivity and longer growing seasons;³
8. result in longer growing seasons at mid- and high latitudes;^{4,5} and
9. increase the range and fecundity of crop pests.⁹

All of these changes will require increased flexibility in resource management.^{61,62,63}

Adaptation for agricultural land use for the next 20–30 years, or to the mid-21st century, will be most effective when decision-making integrates biophysical, social, and economic components. Proactive learning opportunities that integrate experimental and experiential knowledge—such as lessons learned from early adopters—can help enhance decision-making. After all, many adaptations have already been implemented by a subset of producers in this region, providing opportunities for assessment, further development, and adoption. Context-specific decision-making for operations can also be improved through science–management partnerships, which aim to build adaptive capacity while being sensitive to multiple production, conservation, and environmental goals. Transfer of this adaptive knowledge in a timely manner to producers in the field through novel, multipronged communication efforts will assist land managers in more effectively and resiliently responding to the changes to come (see Case Study “Adaptive Rangeland Management”). The climate changes projected over the longer term (through the end of this century) are likely to require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises.^{61,64}

Case Study: Adaptive Rangeland Management

Highly variable precipitation in the Northern Great Plains makes it difficult for managers to balance forage availability with animal demand. An emergent focus is on management strategies that are adaptive rather than prescriptive. But adaptive solutions require collaboration, often among stakeholders with different production and conservation goals. For example, grassbanking, in which ranchers lease land from property owners at a discount in exchange for carrying out conservation-related projects on their pastures, requires management strategies that can successfully deal with this variability. They can also require engagement between different land ownership types, including privately owned land, leased land, state lands, and federal lands. At The Nature Conservancy's Matador Ranch in north central Montana, local ranchers pay reduced grazing fees to graze their cattle on the Matador in exchange for wildlife-friendly and ecologically sound practices on their own operations, where a ranch management plan is required and sodbusting is prohibited. Each year, Conservancy staff and the ranchers develop a grazing plan for the Matador to reach production and ecologically based management goals, including the diverse vegetation structure needed by imperiled grassland birds and greater sage-grouse. In 2017, the Matador Grassbank ranches encompassed over 280,000 acres of private and public leased land. Working cooperatively, the Conservancy and grassbank members improved habitat for imperiled wildlife species on more than 340,000 acres, all while creating conditions that allow for sustainable ranch operations across variable and changing climatic conditions.

Learning how better decisions are made in the face of climate variability is a challenging research topic and one that also requires close collaboration—in this case between stakeholder groups and scientists. Another project, the Collaborative Adaptive Rangeland Management (CARM) experiment, which started in 2012 with a series of meetings involving ranchers, conservation/environmental organizations, and public land managers, is an example of such a research project. Conducted at a ranch-level scale for relevance to producers and managers, the research seeks to determine how adaptive rangeland management can be implemented in a manner that effectively responds to current and changing rangeland and weather/climatic conditions, incorporates active learning, and includes management decisions from a diverse stakeholder group based on quantitative, repeatable measurements collected at multiple spatial and temporal scales. An 11-person stakeholder group determined goals for vegetation, livestock, and wildlife. Specific objectives were developed for each, and testable hypotheses were derived for the scientists. The group also identified the need for baseline data and subsequent monitoring data to inform decisions made within the year, as well as from year to year. Following the implementation of more sustainable grazing management and prescribed fire treatments in 2014, interpretation of the monitoring data regarding progress towards accomplishing the desired objectives provided the opportunity for stakeholders and scientists to engage in shared learning and co-production of knowledge. CARM is a promising model for collaborative research that develops science-based management recommendations for multiple rangeland goals and objectives.

Key Message 3

Recreation and Tourism

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

Ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures and at risk in a changing climate. Recreationists enjoyed roughly 13.1 million days of fishing in the region in 2011, along with 10.8 million days of hunting and 8.7 million days of wildlife-watching. The region contains two dozen national parks, monuments, and historic sites. This subset of outdoor recreationists alone—among a wider population who pursue additional outdoor recreation activities in the region—spent over \$4.9 billion on these activities during 2011 (\$5.2 billion in 2015 dollars).^{65,66,67,68,69}

Climate change affects recreation through three pathways: 1) direct impacts to the ecosystems and wildlife or fish populations of interest (for example, increasing water temperature impacting coldwater fish survival); 2) changes in environmental conditions that directly affect recreationists (for example, increased water temperatures resulting in brief river closures for angling to minimize additional stress on sensitive fish species); and 3) effects of adaptation policies on habitat quality or recreational enjoyment (for example, energy policies that result in higher fuel costs, making distant trips more expensive).⁷⁰ These three pathways have not been fully quantified for most recreational systems, within or beyond the Northern Great Plains, and the third pathway is only speculative—it has not yet been documented in the scientific literature. Scientific understanding is most complete for the first pathway—the extent and ways in which climate change affects ecosystems that support outdoor recreation.⁷⁰

Climate-related impacts are already being felt in the region's terrestrial and aquatic ecosystems, as well as the local economies that depend upon them. Climate-driven changes in snowpack, spring snowmelt, and runoff have resulted in more rapid melting of winter snowpack and earlier peak runoff due to rapid springtime warming.^{71,72,73} These effects have resulted in lower streamflows, especially in late summer.⁷⁴ Lower flows, combined with warmer air temperatures, have caused stream temperatures to rise.^{75,76,77} These conditions are negatively affecting aquatic biodiversity (e.g., Hotelling et al. 2017⁷⁸) and ecosystem functions of riparian areas (areas along the banks of rivers and streams; e.g., Tonkin et al. 2018⁷⁹), with important consequences for local economies that depend upon river-based recreation. For example, higher stream temperatures are accelerating the hybridization and genetic dilution of native trout species

with nonnative trout species.⁸⁰ Similarly, shifts in habitat suitability in favor of warmwater fish species are projected to reduce the value of coldwater fishing in the Northern Great Plains by \$25 million per year under RCP4.5 by the end of the century and by \$66 million per year under RCP8.5 (in 2015 dollars).⁸¹ Higher stream temperatures are already increasing the vulnerability of coldwater fish species to diseases, such as proliferative kidney disease (PKD).^{82,83,84} PKD killed thousands of native mountain whitefish in Montana during 2016, which triggered a month-long closure of 180 miles of the Yellowstone River to all water-based recreation.⁸⁵ Economic impacts to local communities are still being quantified, but initial estimates range from \$360,000 to \$524,000 (in 2014 dollars; range is from \$363,600 to \$529,240 in 2015 dollars).⁸⁶

In the mountainous areas of the region, climate change is impacting snow-dependent ecosystems and economies. In Wyoming and Montana, for example, higher-than-normal winter and fall temperatures and low summer precipitation are enabling severe mountain pine beetle outbreaks in whitebark pine.⁸⁷ Whitebark pine is a keystone species of high-elevation ecosystems, providing a critical seed source for more than 20 wildlife species, creating microenvironments that allow other tree species to establish, and influencing snowpack dynamics.^{88,89} Whitebark pine is also an important cultural resource for some tribes in the region.⁹⁰

In the future, warmer temperatures and changes in precipitation are expected to decrease the extent and duration of snow cover across much of the northern hemisphere. In the mountains of western Wyoming and western Montana, the fraction of total water in precipitation that falls as snow (from October 1 to March 31) is expected to decline by 25% to 40% by 2100 under a lower scenario (RCP4.5).¹⁰ The

last day of the snow season is also expected to arrive earlier in the spring. Under a lower scenario (RCP4.5), it is expected to occur roughly 20 days sooner by 2050 and 30 days sooner by 2100. Under a higher scenario (RCP8.5), it is expected to occur 80 days sooner by 2100.¹⁰ This would negatively affect the region's winter recreation industry, including snowmobiling, cross-country skiing, and downhill skiing.¹¹

Under a lower scenario (RCP4.5), the season length for cross-country skiing and snowmobiling in northwestern Wyoming and western Montana is expected to decline by 20% to 60% by 2090.¹¹ Under the higher scenario (RCP8.5), the projected decline is more severe: 60% to 100%.¹¹ Similar losses in season length are projected for the region's downhill skiing industry—a \$275 million industry.¹¹ The number of visitors to downhill ski areas is, therefore, expected to decline. Under RCP4.5, visitors are projected to decline by 13% by 2050 and 22% by 2090 (holding population constant); under RCP8.5, projected declines are 19% by 2050 and 49% by 2090.¹¹ Similar declines are projected for the region's \$4.6 million cross-country ski industry and \$2.3 million snowmobiling industry (in 2015 dollars).¹¹ Such reductions in visitor numbers would cause ripple effects across the local economies of snow-dependent communities.

At lower-elevation areas of the Northern Great Plains, natural ecosystems are often embedded within agricultural landscapes. Climate-induced land-use changes in agriculture can, therefore, have cascading effects on closely entwined natural ecosystems, such as wetlands,¹² and the diverse species and recreational opportunities they support. Technological and economic forces within agriculture are also driving land-use changes, which accelerate the degradation of wetlands. For example, in South Dakota and North Dakota, changing climatic and market conditions have enabled

agriculture shifts from pasture to small grains, or small grains to corn and soybeans.¹² Nearly 40% of these land-use changes have occurred within 300 feet of neighboring wetlands, reducing the quantity of wetlands and the quality of their ecological functions (see Case Study “Wetlands and the Birds of the Prairie Pothole Region”).⁴⁶ For example, conversion of pasture to cropland or of winter-seeded crops to spring-seeded crops reduces waterfowl nest survival by increasing habitat fragmentation, which makes nests more vulnerable to predation.^{91,92} Tillage in newly converted fields also increases the risk of soil being washed into nearby wetlands, reducing their biological productivity and floodwater storage capacity.⁹³ These changes have cascading effects not only on wetland-dependent waterfowl but also on shorebirds, fish, amphibians, aquatic insects, and plants. Waterfowl hunting and watching are important cultural and economic activities in rural communities of the Northern Great Plains.⁹⁴ In South Dakota alone, hunters spent \$84.7 million in 2015–2016 on migratory bird hunting (in 2016 dollars; \$83.9 in 2015 dollars).⁹⁵

Higher temperatures, reduced snow cover, and more variable precipitation would make it increasingly challenging to manage the region’s valuable wetlands, rivers, and snow-dependent ecosystems to sustain today’s levels of natural amenities and associated recreational opportunities. Federal, tribal, state, and private organizations are undertaking preparedness and adaptation activities, including scenario planning, to discuss current climate-driven challenges and envision future challenges and responses. The North Central Climate Adaptation Science Center, for example, has facilitated scenario planning exercises for southwestern South Dakota in the vicinity of Badlands National Park and for central North Dakota in the vicinity of Knife River Indian Villages National Historic Site.⁹⁶ The Crown Adaptation Partnership—a transboundary

team of scientists and resource managers from the United States, Canada, and Tribes/First Nations—is collaborating on climate change adaptation strategies across multiple jurisdictions to enhance resilience of the Crown of the Continent Ecosystem in northern Montana, southwestern Alberta, and southeastern British Columbia.⁹⁷ Finally, private organizations have been partnering with researchers to develop “payments-for-ecosystem services,” an emerging tool to address land-use change on private agricultural acreage.⁹⁸ This market-based tool, when designed appropriately, can encourage private landowners to provide wetlands, wildlife habitat, pollinator habitat, and other valued ecosystem services rather than converting land to uses that produce fewer ecosystem services.^{99,100}



Photo taken along the White River in Badlands National Park, South Dakota in September 2016. Photo credit: Christian Collins (CC BY-SA 2.0).

The region’s valued ecosystems and recreational opportunities are being affected by climate change to an extent not fully understood, but increasingly being studied. Existing knowledge is primarily based on local and regional case studies, often about specific recreational activities or individual wildlife species. This makes comprehensive assessment a challenge and highlights the need for additional work to fill remaining gaps.¹⁰¹

Case Study: Wetlands and the Birds of the Prairie Pothole Region

The North American Prairie Pothole Region (PPR) is a globally important natural resource, a portion of which covers northern and eastern North Dakota, eastern South Dakota, and far northern Montana. The PPR hosts nearly 120 species of wetland-dependent birds representing 21 families¹⁰² and provides prime nesting and migratory habitat for waterbirds, including ducks and shorebirds.^{103,104} Estimates suggest that 50% to 75% of all North American waterfowl hatch in the PPR.¹⁰⁵



Aerial view of the Prairie Pothole Region in South Dakota. Photo credit: © Patrick Ziegler/iStock/GettyImages.

Climate change is affecting wetlands and the bird species they support in the Northern Great Plains, both directly and indirectly. Changes in spring precipitation affect wetlands directly because spring snowmelt, runoff, and refill influence wetland hydrology (including the number of days with standing water and water depth) and plant cover.¹⁰⁶ A warmer climate, if not offset by enough additional precipitation, will shrink wetland areas in the PPR and reduce waterfowl and shorebird habitat. To offset a temperature increase of 5.4°F (3°C), precipitation would need to increase by 20% or more.¹⁰⁶ If a 5.4°F (3°C) increase in average annual temperature occurs and is only offset by a 10% increase in average annual precipitation, much of the wetland habitat in the PPR will be lost.^{107,108} Densities of wetlands are predicted to decline on average by 20% to 25% by mid-century under a higher scenario (RCP8.5).¹⁰⁹ In a warmer and drier climate, much of the PPR will be too dry to support historical levels of waterfowl nesting and production,¹⁰⁶ with one study projecting that 28 of 29 species studied will lose range in the future under the higher scenario (RCP8.5).¹⁰²

Wetland and bird losses due to climate change are exacerbated by agricultural land-use change in the PPR, with grasslands and pastures being converted to wheat, corn, and soybeans.^{12,46} The degradation of wetland function due to land-use change (Figure 22.4) is driven in part by the increasing profitability of row crops under higher temperatures and increased precipitation in the eastern Dakotas.¹² Land-use change in agriculture to less wetland-friendly crops is also driven by policy and market forces tied indirectly to climate. The ethanol industry's rise in the mid-2000s, for example, contributed to increases in corn prices.¹¹⁰ Rising prices triggered a north-westward expansion of the historical Western Corn Belt into the PPR, and into close proximity to wetlands.⁴⁶ As a result, grassland nesting bird populations are declining faster than any other group of birds in North America.^{111,112} Grassland conversion rates such as these (Table 22.3) have not been seen in the Corn Belt since the rapid mechanization of U.S. agriculture in the 1920s and 1930s.¹¹³

Case Study: Wetlands and the Birds of the Prairie Pothole Region, *continued*

Land-Cover and Land-Use Changes for the Prairie Pothole Region

State	Changes in Area (thousands of acres)		
	Grassland to Corn/Soy	Corn/Soy to Grassland	Grassland Net Loss
Nebraska	309	247	62
North Dakota	320	100	220
South Dakota	632	181	451
Montana	n/a	n/a	n/a
Total	1,261	528	733

Table 22.3: This table shows changes in land cover and land use in the Northern Great Plains portion of the Prairie Pothole Region (PPR), by state, from 2006 to 2011. Note: Montana was not included in the analysis of changes in the PPR cited here, so comparable statistics are not available. Map-based estimates of grassland conversion in Montana from 2008–2012, though not specifically for the PPR, are available from other studies.^{47,114} Source: adapted from Wright and Wimberly 2013.⁴⁶

Reductions in Grassland Area in the Prairie Pothole Region

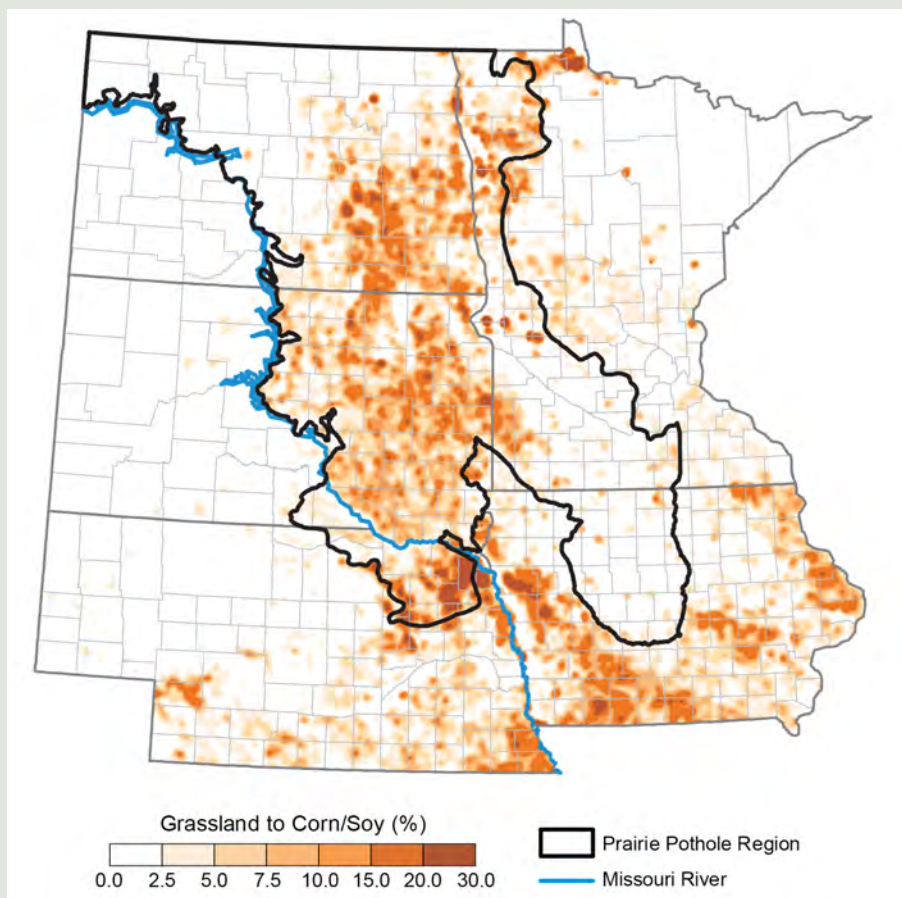


Figure 22.4: The figure shows the loss of grassland to corn/soy between 2006 and 2011 in the eastern states of the Northern Great Plains (Nebraska, South Dakota, and North Dakota), expressed as a percentage of 2006 grassland acres. Outlined in black is the boundary of the U.S. portion of the Prairie Pothole Region, a substantial portion of which was converted from grassland to corn/soy between 2006 and 2011. Source: adapted from Wright and Wimberly 2013.⁴⁶

Key Message 4

Energy

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

Energy resources in the Northern Great Plains include abundant crude oil, natural gas, coal, wind, stored water, and, to a lesser extent, corn-based ethanol, solar energy, and uranium. The infrastructure associated with the extraction, distribution, and energy produced from these resources is vulnerable to the impacts of climate change, including increasing average temperatures and heat waves, decreasing water availability in the summer, and an increase in the frequency and severity of heavy precipitation events leading to floods.¹³

Energy infrastructure vulnerabilities relate to how fuel is transported and how energy is produced, generated, transmitted, and used. For example, railroads and pipelines are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion.¹³ Summer heat waves also damage railroad tracks and are expected to reduce thermoelectric power plant and transmission line capacity,¹³ though estimates of the likelihood, timeframe, or magnitude of such impacts are limited. Higher temperatures are likely to lower the yields of crops used for biofuels while shifting northward the range in which certain biofuel crops (such as corn) can be cultivated.¹³ Biorefineries are

vulnerable to decreasing water availability during drier summers and periods of drought.¹³ Declining water availability in the summer would likely increase costs for oil production operations, which require freshwater resources.¹³ These cost increases will lead either to reduced production or be passed on to consumers. Finally, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer, further stressing the power grid.¹³ Increasing demands for electricity in response to increasing temperatures are projected to increase costs to the power system by approximately \$13–\$18 million per year by 2050 under the higher scenario (RCP8.5) and \$42–\$80 million per year by 2090 under the same scenario (in 2015 dollars).⁸¹

These risks to the energy sector are likely to negatively impact individuals, communities, and the economy, and are also likely to require new planning and preparedness options for the short and long term. While such efforts have already begun, more widespread and coordinated strategies would help maximize risk reduction to the energy sector.

Examples of energy sector resilience solutions include actions like railroad preventive maintenance, upgrades, and reliability standards; water-efficient cooling technologies for thermoelectric power plants, such as recirculating or wet-dry hybrid systems; and programs that reduce total and peak electricity demand.¹³ Such programs, often run by electric utilities, use rebates and cash incentives to encourage customers to purchase more efficient appliances and equipment like lighting, pumps, water heaters, and air conditioners.

The energy sector is also a significant source of greenhouse gas emissions in the Northern Great Plains, as illustrated in Figure 22.6.⁸¹ Methane is released during the production, processing,

transmission, storage, and distribution of natural gas. CO₂ and methane are released during the production, transportation, and refining of petroleum. Coal mining also releases methane. CO₂ is emitted from the combustion of coal and natural gas to produce electricity and from the combustion of petroleum for transportation.¹¹⁷ Natural gas and petroleum systems also emit volatile organic compounds, or VOCs, that contribute to the formation of ground-level ozone pollution. Climate change is generally expected to increase such ozone pollution in the future throughout much of the United States, in part due to higher temperatures and more frequent stagnant air conditions (Ch. 13: Air Quality). Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in ozone are forecast to cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms.¹¹⁸



Floodwaters Surround Nuclear Power Plant in Nebraska

Figure 22.5: Floodwaters from the Missouri River surround the Omaha Public Power District's Fort Calhoun Station, a nuclear power plant just north of Omaha, Nebraska, on June 20, 2011. The flooding was the result of runoff from near-record snowfall totals and record-setting rains in late May and early June (NWS 2012).¹¹⁵ A protective berm holding back the floodwaters from the plant failed, which prompted plant operators to transfer offsite power to onsite emergency diesel generators. Cooling for the reactor temporarily shut down, but spent fuel pools were unaffected.¹¹⁶ Photo credit: Harry Weddington, U.S. Army Corps of Engineers.

Greenhouse Gas Emissions from Fuel Production

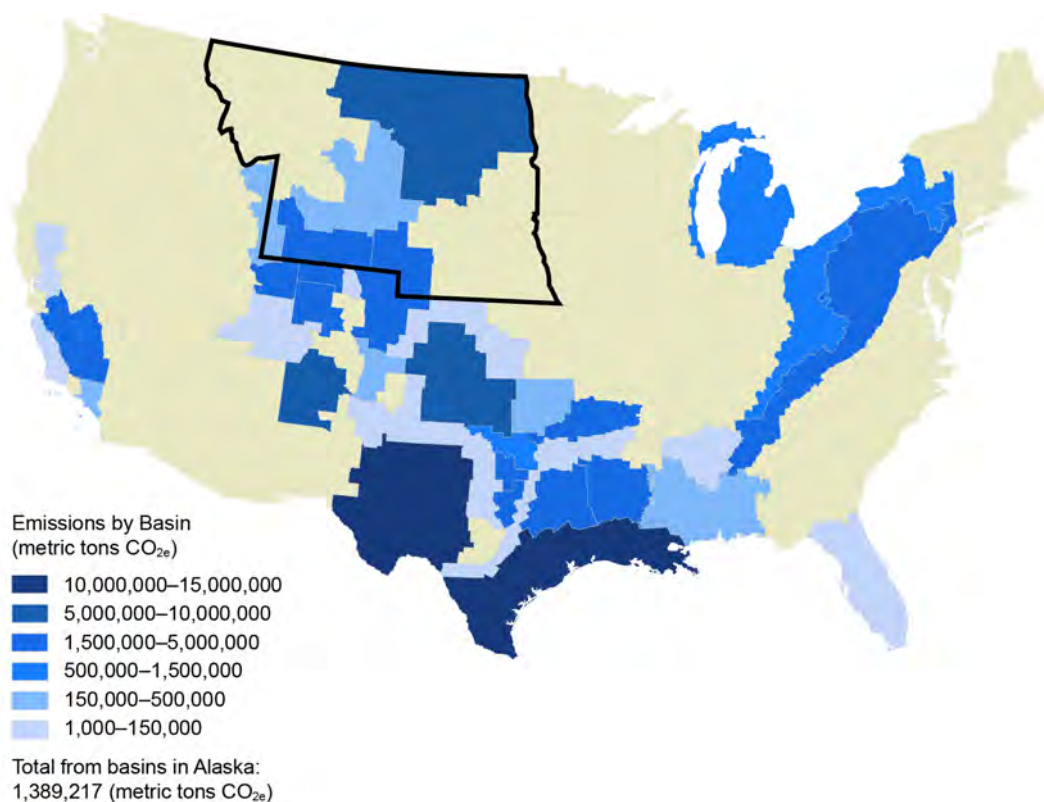


Figure 22.6: Greenhouse gas emissions (shown here in metric tons of carbon dioxide equivalent, or CO_{2e}, per geologic basin) from petroleum and natural gas production facilities in the Northern Great Plains are among the highest in the United States. The data used to produce this map are from EPA's Greenhouse Gas Reporting Program, which only includes facilities that emit 25,000 metric tons of CO_{2e} or more annually.¹¹⁷ Each production facility must provide the total emissions from all their well pads in a geologic basin. Source: adapted from EPA 2017.¹¹⁷

Strategies being employed in the region to reduce greenhouse gas emissions from the energy sector include increasing the performance of coal-fired power plants; offsetting fossil fuel-fired generation with renewable energy; conducting methane leak detection and repair programs using remote sensing technologies at natural gas operations; upgrading the equipment used to produce, store, and transport oil and gas; and demand-side management of electricity use.

Key Message 5

Indigenous Peoples

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

The rich cultural heritage of the Northern Great Plains began with the region's Indigenous peoples who are now in 27 federally recognized tribes, 1 state-recognized tribe in Montana, and several unrecognized tribes in addition to the myriad Native Americans spread throughout the towns, cities, and rural areas of the region

(Figure 22.7). Because tribes and Indigenous peoples are among those in the region with the highest rates of poverty and unemployment, and because many are still directly reliant on natural resources, they are among the most at risk to climate change.^{24,25,27,28,29,30,31}

Indigenous peoples in the region are observing many climate and seasonality changes to their natural environment and ecosystems, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies and medicines, and health and well-being (see Case Study “Crow Nation and the Spread of Invasive Species”).^{14,15,16,17,18,19,20,21,22,23,24,25,26}

Specifically, tribal elders and natural resource managers in the region have observed seasonal changes, such as those in hydrological cycles, phenology, bird migrations, and bear hibernation cycles, as well as reduced availability of traditional plant-based foods and the decline in pine tree species. There is also a mismatch between traditional stories and current climate and seasons.^{14,19} They are also experiencing significant impacts to subsistence fisheries and riparian ecosystem health, including declines in salmon, trout, frogs, and mussels as a result of reduced streamflow and warmer water temperatures.^{19,26,119,120} Extreme heat and declines in traditional plants (such as sage, cottonwoods, and cattails) are already impacting summer outdoor ceremonies when participants fast and camp for days.¹⁹ In addition, tribes are experiencing increased fire frequency and intensity, and climate projections that show increased fire risks for the region are causing concern for the health of forests, wildlife, freshwater systems and fisheries, and human health.^{14,19}

Northern Great Plains Tribal Lands

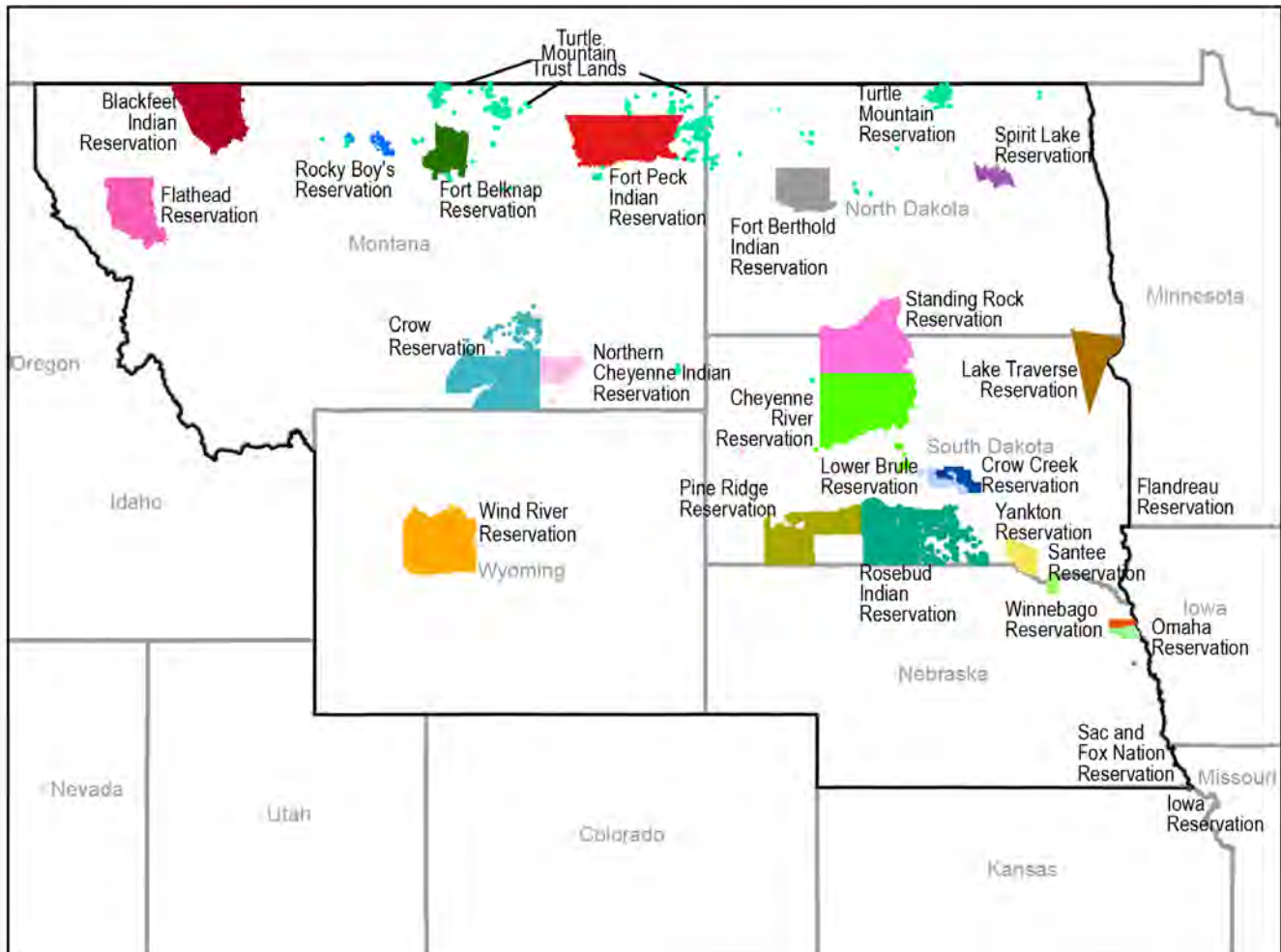


Figure 22.7: The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains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

To the Indigenous peoples of the Northern Great Plains, the Lakota phrase *Mni wiconi* means “water is life.” Water plays significant cultural, religious, and economic roles across tribal communities that transcend consumptive water use. Because water is so integral, these communities are particularly sensitive to climate change impacts on water in the form of extreme flooding and droughts, changes in snowpack, and changes in the timing of precipitation events. These climate sensitivities, along with substandard water infrastructure and complex institutions and water rights, all combine to create water insecurity.^{14,18,19,20,23,24,28,120,121,122,123,124} In the Northern Great

Plains, just under 29,000 (76%) Indigenous households are in need of new or improved sanitation facilities, and approximately 5,000 households lack safe water supply, sewage facilities, or both.¹²⁵ The total cost to remediate sanitation facility deficiencies in the region was estimated at around \$280 million according to a 2015 annual report from the Indian Health Service.¹²⁵ Climate change has already begun to exacerbate the problem of disruptions to water supplies from decreased water availability, as happened in 2003 when Standing Rock Reservation ran completely out of water during drought.²⁸

Case Study: Crow Nation and the Spread of Invasive Species

A warming climate is projected to hasten the spread of invasive species within riparian ecosystems.^{134,137,138,139} Indigenous populations who harvest and hold sacred flora and fauna along rivers within the semiarid region of south central Montana are particularly vulnerable.¹⁴⁰ Post-reservation settlement of Treaty Tribes and multiple land policies aimed at assimilation of Native American Tribes in the United States created a checkerboard of land ownership within reservation boundaries. The Apsaalooké, or Crow, Reservation was established after the Fort Laramie Treaty of 1886 and is located within the mountains and valleys along the Little Bighorn and Big-horn Rivers in south central Montana.¹⁴¹ Promotion of agriculture in the late 19th century, along with the establishment of divergent dams for floodplain irrigation, resulted in decreased water flows, affecting the natural pulse of these river systems and their associated native riparian species. Cascading effects of river regulation, along with intentional planting of the invasive species Russian olive (*Elaeagnus angustifolia* L.) during the Indian Emergency Conservation Work era of the 1930s, have drastically altered natural vegetation within these watersheds (Figure 22.8). These complex networks of policy and culture determine the ways in which land and riparian regimes were drastically changed. The resulting conditions favored invasive plants and ecosystem degradation.¹⁴²

The Apsaalooké, or Crow, people regularly harvest riparian plant species for food, ritual, and ceremonial uses. For example, plains cottonwood (*Populus deltoides*, Marsh) and willow (*Salix* sp. L.) are used for ceremonial (sweat lodge and Sun Dance) purposes. Crow Elders indicated that they must travel on average more than 15 miles farther now than they did 25 years ago to locate cottonwoods of specific sizes. They also find it difficult to locate and harvest traditional food sources such as chokecherry (*Prunus americana* L.) and buffalo berry (*Shepherdia argentea* Pursh., Nutt.). What was once a cottonwood- and willow-dominated river system is now dominated by Russian olive. Populations of salt cedar are likewise increasing along both the Bighorn and Little Bighorn Rivers and associated floodplains. Projections using habitat species distribution models suggest that Russian olive plants will continue to spread in the next 10 years as a result of increasing temperatures and precipitation (Figure 22.8). Continued spread of Russian olive species ultimately threatens the ability of the Crow people to harvest culturally important riparian species that provide subsistence, medicine, and plant species used in ceremony.¹⁴⁰



The Russian olive invasion is a challenge throughout the Northern Great Plains. Here, the trees grow on ranchland on the Crow Indian Reservation. Photo credit: Kurrie Jo Small.

Case Study: Crow Nation and the Spread of Invasive Species, *continued*

Projected Expansion of Russian Olive Habitat

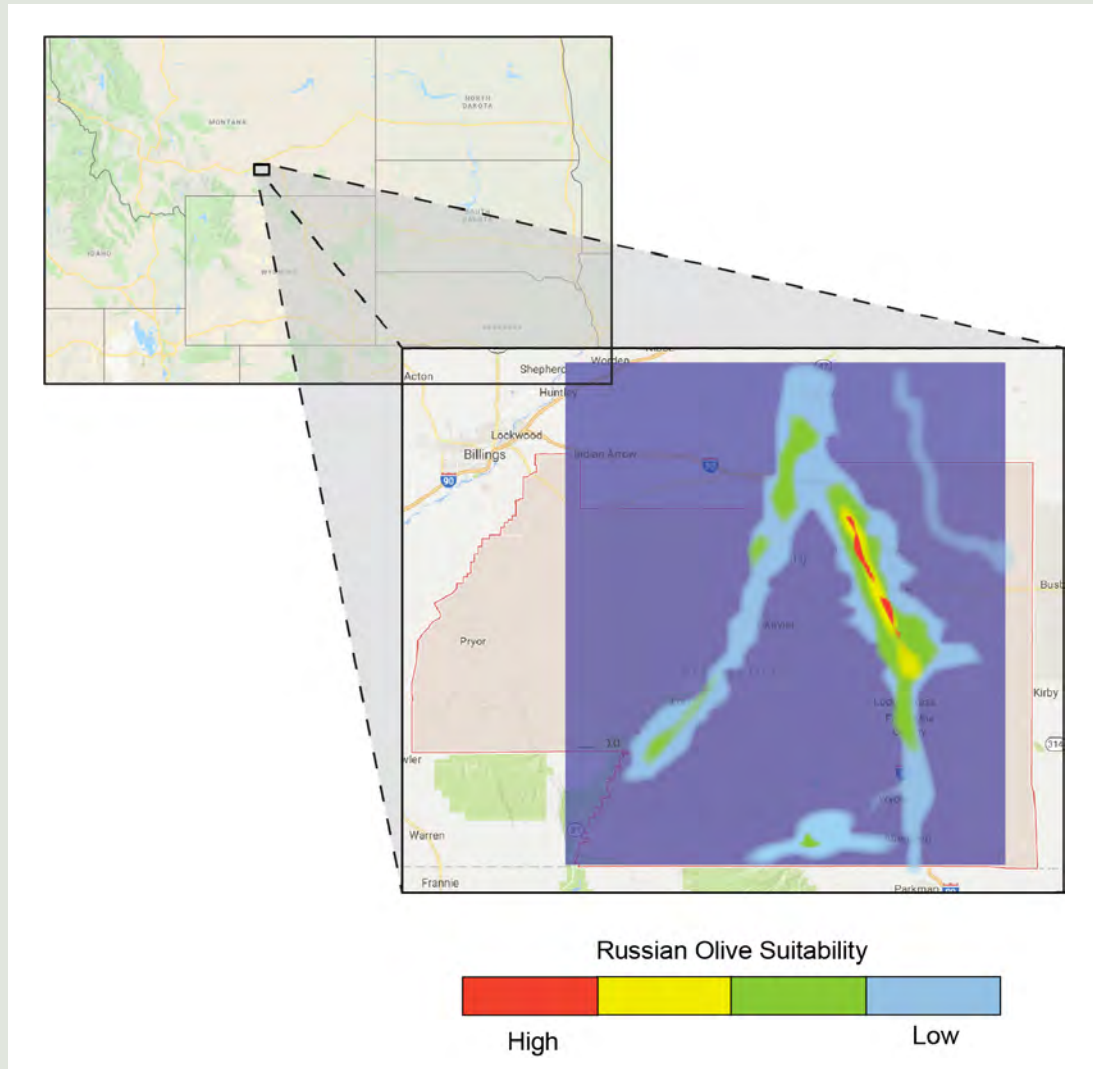


Figure 22.8: The map shows the projected expansion by 2021 of Russian olive habitat. Warmer colors indicate favorable habitat for future spread of Russian olive based on mapped presence points along the Little Bighorn and Bighorn Rivers within the Crow Indian Reservation in south central Montana. The Crow Reservation is outlined and shaded in red. Purple areas are outside of the suitability zone. Source: University of Arizona. Map data © 2018 Google, INEGI.

Reservation Irrigation Projects: Deferred Maintenance and Replacement Costs

Irrigation Project	Deferred Maintenance for FY 2014	Replacement Value
Blackfeet	\$26,000,000	\$50,000,000
Flathead	\$82,000,000	\$237,000,000
Fort Belknap	\$8,000,000	\$19,000,000
Fort Peck	\$13,000,000	\$33,000,000
Crow	\$17,000,000	\$59,000,000
Wind River	\$30,000,000	\$93,000,000
Total	\$176,000,000	\$491,000,000

Table 22.4: This table shows deferred maintenance and replacement costs for U.S. Bureau of Indian Affairs irrigation projects on six Northern Great Plains reservations (in 2014 dollars). Source: U.S. Government Accountability Office 2015.¹²⁶

Agriculture, particularly livestock ranching, is a primary tribal livelihood in the region, and warmer temperatures and changes to water cycles (for example, reduced snowpack, earlier transition from snow to rain, and reduced or early runoff) pose a large threat and are already drying soils, reducing forage production, increasing livestock stress, and reducing water availability for irrigation systems throughout the region.^{20,120} Reservations in the region would require a combined \$176 million in maintenance or \$491 million to replace neglected and failing Bureau of Indian Affairs irrigation systems (Table 22.4).¹²⁶ High leakages and inefficiencies in these systems hinder effective management of water and irrigation systems for climate change.²⁰

Tribes have unique water rights and layers of relevant state and federal laws (for example, the Winters Doctrine and state water rights adjudication, and Prior Appropriation laws in the West). Climate change impacts on water resources are very likely to be compounded by these legal complexities, especially in cases where state water laws supersede tribal water codes and water rights during times of scarcity, such as at Wind River Reservation, where the Wyoming Supreme Court ruled that the state has primary authority.^{20,123,127,128} Indigenous people in the region are also very concerned

about the consequences of major oil pipelines passing through the region. Their concerns are in part focused around potential leaks, which would impact water resources already stressed by climate change. This concern is further intensified by the reality that climate change is projected to damage infrastructure in the region, including pipelines, through extreme storm or precipitation events that cause flooding.^{54,56,121}

Disaster management is another area of great concern for the Northern Great Plains tribes. Over the last two decades, tribes have experienced unusually catastrophic fires, floods, and droughts that are already straining response capacities,²⁵ and climate change is expected to increase the need for the ability to fight fires, floods, and droughts.^{14,16,25,129,130,131} Severe droughts in this century have resulted in serious impacts, such as tribal ranchers liquidating herds and reservations possessing no water at all.²⁸ Extreme hydrological events on the region's reservations are also happening in quick succession, such as the 2011 floods followed by severe drought and fire in 2012.^{19,20,25,28} Each event strains the response capacity, and for the many tribes struggling with a lack of disaster preparedness, successive events compound the challenge.^{25,28} This has widespread impacts on tribal economies and

livelihoods, domestic and municipal water supplies, and health and well-being.

Many climate adaptations are underway in Northern Great Plains Indigenous communities, but tribes also face unique legal and regulatory barriers because of post-colonial resettlement and reservation impacts of land fragmentation and uneven regulation by federal agencies. For example, the trust relationship with the Federal Government, where the Federal Government holds the titles of tribal lands “in trust” for the tribes, requires federal permission for many aspects of land and resource management.^{14,15,16,17,18,20,25,131,132,133,134,135}

Outside of these limitations, however, the tribes do have control over the reservations’ built environment and housing. For example, the Oglala Lakota Nation (Pine Ridge) in South Dakota has created a sustainability plan that includes off-grid, climate-resilient housing and sustainable agriculture.^{16,17,122,136} Other climate adaptation examples include Flathead Reservation’s strategic climate planning for multiple sectors and species of cultural and economic importance; several South Dakota tribes’ climate vulnerability assessment and drought planning; Wind River Reservation’s drought assessment and preparedness; Northern Cheyenne Tribe’s Integrated Resource Management Planning that will include climate change; and Fort Belknap’s climate adaptation plan, which integrated planning with fire, forestry, and invasives management.^{14,20,25} The InterTribal Buffalo Council also has drought and climate adaptation grants to prepare tribal bison herd managers in the region and beyond for climate

impacts to bison pastures and water sources. There are multiple tribal initiatives that focus on climate and Indigenous knowledge-based education, outreach, and information sharing between tribes. For example, the Northern Cheyenne Indigenous land-based science learning program offers apprenticeships for youth interested in bio-cultural restoration science. The program, which sits in the tribe’s Department of Environmental Protection and Natural Resources, aims to increase tribal knowledge around Indigenous and western sciences and thus enable youth to reclaim their responsibility to the land. Also, the Blackfeet and Confederated Salish and Kootenai Tribes collaborated on a regional workshop with First Nations throughout the region to share ideas and strategies and provide support for tribal climate adaptation planning.²⁵ Tribes are increasingly drawing on their deep, place-based connections to natural cycles and Indigenous knowledge, combined with western technical sciences, to respond to and prepare for climate change.^{14,15,16}

Acknowledgments

USGCRP Coordinators

Allyza Lustig

Program Coordinator

Kristin Lewis

Senior Scientist

Opening Image Credit

Cameron, Montana: Paul Cross/U.S. Geological Survey.

Traceable Accounts

Process Description

The chapter lead (CL) and coordinating lead author (CLA) developed a list of potential contributing authors by soliciting suggestions from the past National Climate Assessment (NCA) author team, colleagues and collaborators throughout the region, and contributors to other regional reports. Our initial list of potential authors also included CL nominees submitted to the U.S. Global Change Research Program (USGCRP). The CL and CLA discussed the Northern Great Plains, which was part of the larger Great Plains region for the Third National Climate Assessment (NCA3), with each of these nominees and, as part of that discussion, solicited suggestions for other nominees. This long list of potential contributing authors was pared down by omitting individuals who could not contribute in a timely fashion, and the list was finalized after reconciliation against key themes within the region identified by past NCA authors, the CL and CLA, and contributing author nominees. The team of contributing authors was selected to represent the region geographically and thematically, but participants from some states who had agreed to contribute were eventually unable to do so. Others were unable to contribute from the start. The author team is mostly composed of authors who did not contribute to NCA3.

The CL and CLA, in consultation with past NCA authors and contributing author nominees, identified an initial list of focal areas of regional importance. The author team then solicited input from colleagues and regional experts (identified based on their deep ties to scientific and practitioner communities across the region) on their thoughts on focal areas. This list informed the agenda of a region-wide meeting held on February 22, 2017, with core locations in Fort Collins, Colorado, and Rapid City, South Dakota. The main purpose of this meeting was to seek feedback on the proposed list of focal areas. With this feedback, the author team was able to refine our focal areas to the five themes comprising the Key Messages of the Northern Great Plains regional chapter. Of these, recreation/tourism is a focus area that is new from NCA3.

Key Message 1

Water

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

Description of evidence base

Multiple lines of research have shown that as a result of its high aridity, changes in water availability in the Northern Great Plains region are highly sensitive to small changes in climate.^{35,36,143,144} Despite large differences in climate from the western mountains to the eastern plains, the reliance

upon reservoir storage to regulate water supplies is ubiquitous—to provide water during times of drought and to mitigate flood waters during deluges.

Natural reservoirs, groundwater, and snowpack are at risk to varying degrees. Reservoir vulnerability was recently analyzed to assess sustainable pumping rates,⁴² while snow and especially glaciers appear to be in steady decline in recent decades,³⁸ attributed to global climate warming³⁹ that is projected to continue.¹⁴⁵

Major uncertainties

While there is high confidence in future increases in temperature, uncertainties exist as to the changes in precipitation and runoff. Perhaps most important are the uncertainties in the degree of precipitation variability from year to year and within season (based on information dating to the 1950s).^{35,52} These uncertainties are very likely to overwhelm the projected modest increases in precipitation.

Uncertainties exist in agricultural demands for water, reservoir operation protocols, and changes in extreme events.

Description of confidence and likelihood

There is *high confidence* that temperatures will rise in the region, which will *likely* produce less snowfall and smaller mountain snowpacks. There is *very high confidence* in the downstream consequences of these changes.

Key Message 2

Agriculture

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

Description of evidence base

Several lines of research have shown that agricultural productivity is likely to increase in rangelands across the region with increasing atmospheric carbon dioxide (CO₂) and warming,^{3,7,8} with no yield changes likely for small grain crops (for example, wheat) and yield reductions likely for row crops (for example, corn) in dryland croplands.⁶ The competitive ability of weeds (primarily perennial forbs such as *Linaria dalmatica* and annual grasses such as *Bromus tectorum*) is likely to increase as well, with corresponding impacts to forage production,^{1,2} as phenology is altered^{57,58} and the growing season lengthens.^{4,5} Forage quality is expected to decline,^{3,59,60} and crop yields

are likely to decrease if extreme temperature events (high daytime highs or nighttime lows) occur during critical pollination and grain fill periods.⁹

Numerous lines of research have addressed adaptation strategies for various parts of the agricultural sector^{9,61,63,146,147,148}

Major uncertainties

While there is high confidence in future increases in temperature, uncertainties exist as to the changes in extreme events, including the spatiotemporal aspects of high-intensity rainfall events, snowstorms, and hailstorms. Perhaps most important are the uncertainties in the degree of precipitation variability from year to year³⁵ that influence decision-making calendars for agricultural producers.

Description of confidence and likelihood

There is *very high confidence* that longer growing seasons have already benefited agriculture in parts of the Northern Great Plains. There is *very high confidence* that increases in temperatures and atmospheric CO₂ will *likely* increase production potential for the agricultural sector in the short term (the next 10–20 years) and that current adaptations already being implemented by a subset of producers in this region provide opportunities for assessment, further development, and adoption by the larger population of agricultural managers. There is *very high confidence* that rising temperatures and changes in extreme weather events are *very likely* to have negative impacts on parts of the region. Over the longer-term (through the end of the 21st century), predicted climate changes may require transformative changes in agricultural management, including regional shifts of agricultural practices and enterprises (*very likely, high confidence*).^{61,64}

Key Message 3

Recreation and Tourism

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

Description of evidence base

State-level surveys, conducted roughly every five years, have consistently documented that the public spends millions of days each year (over \$30 million in 2011) participating in nature-based recreation activities in the Northern Great Plains (e.g., U.S. Department of the Interior and U.S.

Department of Commerce 2008, 2013a, 2013b, 2014a, 2014b^{65,66,67,68,69}). The implications of climate change for outdoor recreation, and tourism more broadly, have been studied extensively around the globe (see summaries in Scott et al. 2012, Rosselló and Santana-Gallego 2014, Brice et al. 2017^{101,149,150}). Region-specific studies are only a small subset of this large body of literature, so our understanding of potential impacts of climate change on outdoor recreation in the Northern Great Plains is sometimes inferred from other regions with similar characteristics (e.g., Hari et al. 2006⁸³). Region-inclusive studies are available (e.g., Wobus et al. 2017¹¹) for the sectors most obviously affected by climate change (such as winter recreation). Our understanding is most complete about the implications of climate change for the ecosystems upon which outdoor recreation in the Northern Great Plains depends.⁷⁰ For example, the implications of climate change for wetlands and waterbirds in the Prairie Pothole Region, upon which much bird hunting and bird watching in the region depend,^{104,105} have been studied extensively over the past several decades (e.g., Johnson and Poiani 2016, Wright and Wimberly 2013^{46,106}). The role of agricultural land-use change (as a function of climate change as well as complex technological, policy, and market factors) in the degradation of wetland function in the region—for example through increased soil erosion and resulting wetland sedimentation or upland habitat fragmentation and resulting increases in waterfowl nest predation—has also been thoroughly assessed (e.g., Rashford et al. 2016, Sofaer et al. 2016^{12,109}).

Major uncertainties

Climate change is expected to disrupt local economies that depend on winter-based or river-based recreational activities. However, the magnitudes of these effects are uncertain. This is due largely to uncertainties about the preferences of recreationalists and the extent to which they will adapt by shifting the timing and location of their activities or by substituting towards a different set of recreational activities. For example, although climate change will make it more difficult to supply high-quality downhill skiing opportunities, this effect will be stronger in lower-elevation areas. Therefore, some skiers might adapt by simply traveling to higher-elevation downhill ski areas. Others might compensate for the shorter ski season at their favorite lower-elevation mountain by shifting some of their recreational time to an alternative outdoor activity, such as winter mountain biking. Given the potential diversity of individual preferences for adapting outdoor recreation activities to climate change, it is challenging to project with certainty the future potential impacts to recreation-dependent economies, but the impact will be larger and more immediate for some industries and companies (e.g., low-altitude ski resorts).

Another source of uncertainty is the reliance, in some cases, on scientific studies from other geographic locations to infer what the impacts of climate change might be for ecosystems, species, or recreationalists within the Northern Great Plains. For example, the effects of increased stream temperature on the susceptibility of coldwater fish species to diseases in the region are based largely on studies conducted in European coldwater fisheries.

Regarding wetlands in the Prairie Pothole Region, uncertainty about their abundance in the future arises from uncertainty about future government policies that would either exacerbate or mitigate climate-induced losses. For example, future versions of the Farm Bill may contain language that directly encourages wetland preservation (e.g., through conservation-compliance requirements) or unintentionally leads to wetland degradation (e.g., through higher subsidies for row crop insurance).

Description of confidence and likelihood

We know with *very high confidence* that ecosystems across the Northern Great Plains provide recreational opportunities and other valuable goods and services. We know with *very high confidence* that climate change is *very likely* affecting abiotic factors that influence these ecosystems, such as snowfall, spring snowmelt, runoff, and stream temperatures. There is *high confidence* that these abiotic factors are *likely* to affect high-elevation ecosystems and riparian areas in the Northern Great Plains. Greater confidence could be gained by conducting studies specifically within the Northern Great Plains, as opposed to drawing inferences from studies conducted in other regions of the world with similar characteristics. The consequences of ecosystem changes for local economies in the region that depend on winter-based or river-based recreational activities are currently being debated in the scientific literature, due to uncertainty about potential individual behavioral responses to changes in the recreational environment. Based on a limited number of case studies, effects of climate change on outdoor recreation-based economies are *as likely as not* to be negative, but this is only known with *medium confidence*. We know with *very high confidence*, however, that some natural ecosystems that local economies depend upon—in this specific case, wetlands in the Northern Great Plains—are *likely* to be negatively affected by climate-induced changes in agricultural land use. In turn, we know with *high confidence* that wetland declines will *very likely* harm the diverse species and recreational amenities they support. Uncertainty about future policies that could influence agricultural land-use decisions and wetland conservation outcomes precludes a higher confidence level or higher likelihood.

Key Message 4

Energy

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

Description of evidence base

Fossil fuel and renewable energy production/distribution infrastructure is expanding within the Northern Great Plains, including oil and natural gas pipelines, natural gas compressor stations and storage tanks, natural gas processing plants, natural gas-fired power plants, high-voltage power lines and substations, wind farms, and even a new oil refinery and a new biorefinery in recent years (both began operations in 2015).

A number of oil and natural gas pipelines are being constructed or have been completed in recent years. In particular, the Dakota Access Pipeline began commercial service June 1, 2017, transporting crude oil from the Bakken/Three Forks production areas in North Dakota, through South Dakota and Iowa, to Paksota, Illinois. While pipelines are vulnerable to damage or disruption from heavy precipitation events and associated flooding and erosion,¹³ their increased use could

eliminate hundreds of rail cars and trucks needed to transport crude every day. This reduces the exposure of these modes of transportation to rising temperatures, heat waves, and floods.¹³ Other oil and gas production and distribution infrastructure is similarly vulnerable to heavy precipitation events and flooding.

The region relies on rail lines to transport coal, and these lines are vulnerable to rising temperatures, heat waves, and floods.¹³ There is ample evidence of rail line vulnerability to extreme weather.¹⁵¹

Damage to thermoelectric power plants and electric power transmission lines from extreme weather such as heat waves and wildfires has been documented, and the risk is expected to increase.^{13,152}

The U.S. Department of Energy (DOE) Energy Risk Profiles (1996–2014) highlight the risks to energy infrastructure in the United States from natural hazards. For example, in North Dakota, thunderstorms and lightning had the highest frequency of occurrence and property loss during this timeframe. DOE also has a series of comprehensive documents on U.S. energy sector vulnerabilities to climate change^{13,153} that identify important climate-related vulnerabilities for fuel transport, electricity generation, and electricity demand.

There is substantial evidence that the energy sector is a significant source of greenhouse gases that contribute to climate change, in particular from power plants, oil and gas systems, and refineries.¹¹⁷

Major uncertainties

Cold waves are projected to be less intense in the future, reducing the risk of disruptions from cold to energy infrastructure.¹³

There is not yet substantial agreement among sources as to how a changing climate will ultimately affect wind resources in the United States in general and in the Northern Great Plains in particular.¹⁵³

Projected increases in precipitation in the Northern Great Plains are likely to benefit hydropower production, but this will vary by location. For example, it is known that in the Columbia River Basin, decreasing summer streamflows will reduce downstream hydropower production, and increasing winter and early spring streamflows will increase production.¹³ In the Missouri River Basin, projected seasonal declines in precipitation in the southern and western portion of the region are likely to reduce the water available to generate hydropower.¹³

Biofuel feedstocks from crops and forage grown in the Northern Great Plains are vulnerable to climate change, but the net impacts on biofuel production are uncertain.¹³

It is well understood that ground-level ozone (O₃) is created by chemical reactions between volatile organic compounds in the presence of sunlight and would be exacerbated by climate change. What is less understood is the sensitivity of regional climate-induced O₃ changes, and the science of modeling climate and atmospheric chemistry to understand future conditions.

Description of confidence and likelihood

There is *high confidence* that climate change and extreme weather events will *likely* put energy supply and infrastructure of various types at risk. There is *high confidence* that the energy sector is a *very likely* a significant source of greenhouse gases contributing to climate change. There is *very high confidence* that volatile organic compounds contribute to climate change and ground-level ozone pollution, and it is *likely* that this will worsen in the future in some areas.

Key Message 5

Indigenous Peoples

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

Description of evidence base

Multiple lines of research have shown that hydrological changes and changes in extremes have resulted in deleterious impacts to Indigenous peoples.^{14,18,19,20,23,24,28,121,122,123,124} During times of drought, decreased water availability negatively impacts tribal communities and livelihoods such as ranching, and already stressed water systems and infrastructure do not provide the necessary water to sustain Indigenous communities and reservations.^{20,28,154}

Major uncertainties

The impacts of climate change in the Northern Great Plains are expected to increase risks to Indigenous reservations, communities, and livelihoods. However, there is uncertainty about how Indigenous people will be able to respond. Much of this uncertainty is due to unsettled water rights, multijurisdictional complexities, and federal funding and policies.

Description of confidence and likelihood

There is *very high confidence* that rising temperature and increases in flooding, runoff events, and drought are *likely* to lead to increases in impacts to reservations and other Indigenous communities. There is *very high confidence* that climate changes are already resulting in harmful impacts on tribal economies, livelihoods, and culture. However, the actual impacts and response capacities will depend on the response of regulatory systems and funding amounts.

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Southern Great Plains

Federal Coordinating Lead Author**Bill Bartush**

U.S. Fish and Wildlife Service

Chapter Lead**Kevin Kloesel**

University of Oklahoma

Chapter Authors**Jay Banner**

University of Texas at Austin

John Nielsen-Gammon

Texas A&M University

David Brown

USDA-ARS Grazinglands Research Laboratory

Mark Shafer

NOAA-RISA Southern Climate Impacts Planning Program

Jay Lemery

University of Colorado

Cecilia Sorensen

University of Colorado

Xiaomao Lin

Kansas State University

Sid Sperry

Oklahoma Association of Electric Cooperatives

Cindy Loeffler

Texas Parks and Wildlife Department

Daniel Wildcat

Haskell Indian Nations University

Gary McManus

Oklahoma Climatological Survey

Jadwiga Ziolkowska

University of Oklahoma

Esther MullensDOI South Central Climate Adaptation Science
Center**Review Editor****Ellu Nasser**

Adaptation International

Technical Contributors are listed at the end of the chapter.

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Key Message 1

Whooping cranes in the Aransas National Wildlife Refuge in Texas

Food, Energy, and Water Resources

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

Key Message 2

Infrastructure

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

Key Message 3

Ecosystems and Ecosystem Services

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

Key Message 4

Human Health

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

Key Message 5

Indigenous Peoples

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

Executive Summary



The Southern Great Plains experiences weather that is dramatic and consequential; from hurricanes and flooding to heat waves and drought, its 34 million people, their infrastructure, and economies are often stressed, greatly impacting

socioeconomic systems. The quality of life for the region's residents is dependent upon resources and natural systems for the sustainable provision of our basic needs—food, energy, and water. Extreme weather and climate events have redistributed demands for consumption, production, and supply across the region. Adaptation strategies that integrate climate services and early warning systems are improving our abilities to develop sustainable infrastructure

and increase agricultural production, yet include the flexibility needed to embrace any changing demand patterns.

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

With climate change, terrestrial and aquatic ecosystems, and species within them, have winners and losers. Those that can adapt are “increasers,” while others cannot, resulting in impacts to traditional services and the livelihoods of the people

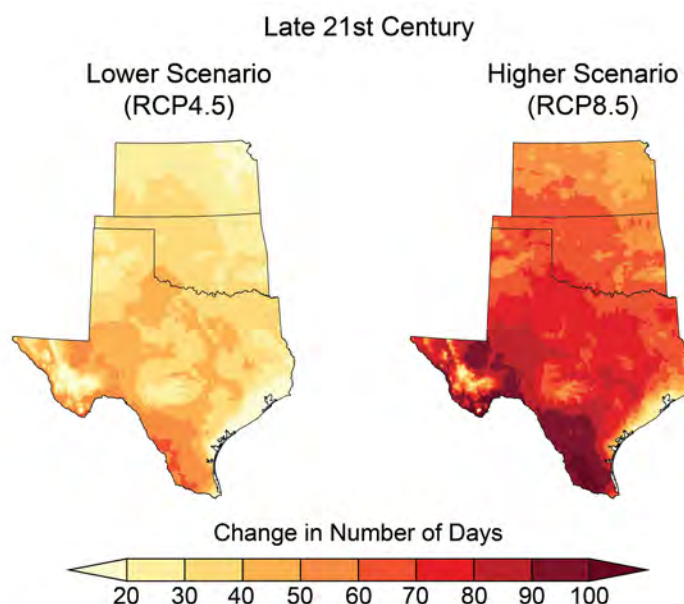
who depend on those resources. The warming of coastal bay waters has been documented since at least the 1980s, and those increases in water temperature directly affect water quality, leading to hypoxia, harmful algal blooms, and fish kills—thus lowering the productivity and diversity of estuaries. Natural wetlands like the playa lakes in the High Plains, which have served for centuries as important habitat for migrating waterfowl, are virtually nonexistent during drought.

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

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

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify.^{1,2} Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather,³ including an increase in the instances of larger hail sizes in the region by 2040,⁴ but changes are unlikely to be uniform across the region, and additional research is needed.

Projected Increase in Number of Days Above 100°F



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

Background

The Southern Great Plains, composed of Kansas, Oklahoma, and Texas, experiences weather that is dramatic and consequential. Hurricanes, flooding, severe storms with large hail and tornadoes, blizzards, ice storms, relentless winds, heat waves, and drought—its people and economies are often at the mercy of some of the most diverse and extreme weather hazards on the planet. These events cause significant stress to existing infrastructure and socioeconomic systems and can result in significant loss of life and the loss of billions of dollars in property.

Climate conditions in the Southern Great Plains vary dramatically from the arid, high-elevation borders with the mountainous states of Colorado and New Mexico on the west, to the humid states of Missouri, Arkansas, and Louisiana in the Mississippi River valley on the east. Average annual precipitation ranges from less than 10 inches in the western reaches of the region to over 60 inches in the southeastern corner (Figure 23.1).

A large west-to-east contrast in surface water availability results, with large reservoirs in eastern parts of the region and few reservoirs in the west. Except for the Missouri River (a portion of the border for the Southern Great

Monitoring Precipitation Across the Southern Great Plains

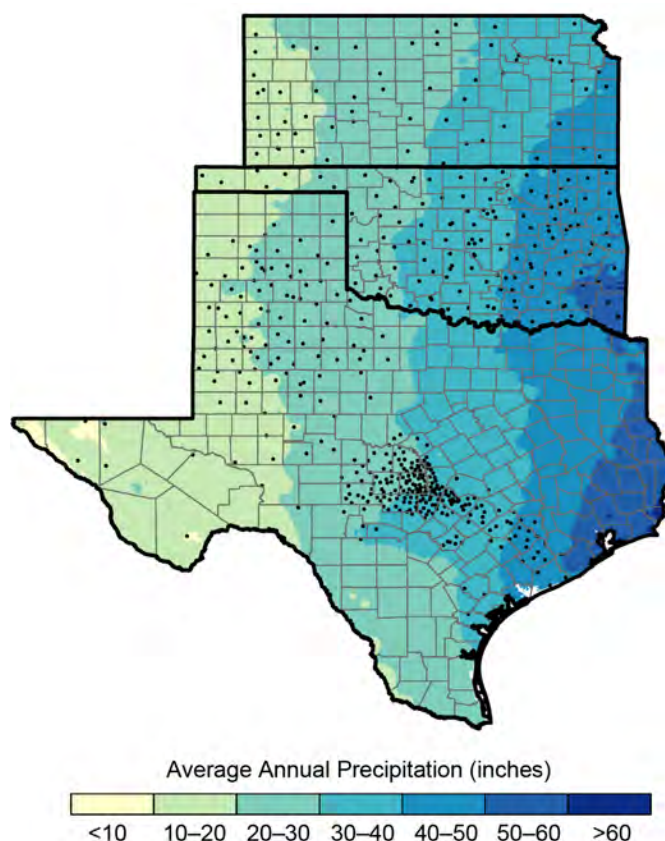


Figure 23.1: The Southern Great Plains is characterized by a pronounced east–west gradient of precipitation, with wetter conditions prevailing to the east and arid conditions to the west. Precipitation monitoring is critical in this region; state-level Mesonet station networks in Kansas, Oklahoma, and Texas are shown here to illustrate a key aspect of current monitoring capacity. Sources: NOAA NCEI, CICS-NC, and ERT Inc. Data from PRISM Climate group, Oregon State University, <http://prism.oregonstate.edu>, created July 10, 2010.

Plains), the Arkansas River, and the upper reaches of the rivers such as the Rio Grande, rivers in the region do not draw from mountain snowpack and are sensitive to seasonal rainfall amounts. The region is vulnerable to periods of drought, historically prevalent during the 1910s, 1930s, 1950s, and 2010–2015, and periods of abundant precipitation, particularly the 1980s and early 1990s. The region has experienced an increase in annual average temperature of 1°–2°F since the early 20th century, with the greatest warming during the winter months.

With the Gulf of Mexico to its southeast, the coastal Southern Great Plains is vulnerable to hurricanes and sea level rise. Relative sea level rise along the Texas Gulf Coast is twice as large as the global average, and an extreme storm surge in Galveston Bay would threaten much

of the U.S. petroleum and natural gas refining capacity. Variations in freshwater flows and evaporation affect the salinity of bays and estuaries along the coast and have the potential to alter coastal ecosystems and affect the fishing industry. Tropical cyclones are also responsible for exceptional rainfall rates in the region. The U.S. record for greatest single-day rainfall is 43 inches, set in Alvin, Texas, in July of 1979, as Tropical Storm Claudette moved through the area. Houston, Texas, in particular, experienced several record-breaking floods in 2015, 2016, and 2017, with Hurricane Harvey rewriting the continental U.S. record for total rainfall from a tropical cyclone. Cedar Bayou, Texas (30 miles from Houston), recorded 51.88 inches of rain during the multi-day onslaught of Hurricane Harvey (see Box 23.1 for further discussion).

Box 23.1: Hurricane Harvey

Hurricane Harvey was a Category 4 hurricane on the Saffir–Simpson scale when it made landfall on the central Texas coast near Rockport late in the evening of August 25, 2017. It then moved inland, stalled, and eventually moved back over the coastal Gulf of Mexico waters before making landfall a final time as a tropical storm several days later in southwestern Louisiana.

Preliminary damage estimates place Harvey as one of the two most costly U.S. natural disasters in inflation-adjusted dollars, rivaling Hurricane Katrina. Flooding from Harvey resulted in the overflow of sewage systems and breaches at numerous waste treatment facilities,⁵ resulting in untreated infectious human waste entering surface waters and resulting in a spike in skin and gastrointestinal infections.⁶

Widespread flooding affected dozens of communities, including those in the Houston and Beaumont metropolitan areas. Immediate effects included deaths from drowning and trauma that claimed the lives of at least 63 individuals. Additionally, more than 30,000 people were evacuated. Displacement of patients from their communities and healthcare providers led to interruptions in medical treatment. Texas has one of the lowest rates of health insurance in the country, and more than 11% of the population of Texas is diabetic.⁷ Additionally, chronic kidney disease rates in Texas are higher than the national average, with a prevalence of over 17% in the adult population, and 1,524 per one million inhabitants require routine dialysis.⁷ In the aftermath of the hurricane, dialysis centers struggled with staffing shortages, and centers in outlying areas worked around the clock to attempt to meet the needs of evacuated patients.⁸ Hospitals and pharmacies faced critical shortages of essential medications (including insulin and respiratory inhalers) due to the inability of suppliers to make deliveries. Hospitals faced critical power shortages and loss of indoor air and temperature controls. At least 15 area hospitals evacuated their patients.⁹

Box 23.1: Hurricane Harvey, *continued*

Based on past trends and recent sea surface temperatures, the heaviest rainfall amounts from intense storms such as Harvey are about 5%–7% greater now than what they would have been a century ago.¹ As discussed in detail in Chapter 2: Climate, several studies have already quantified the human contribution to the record-breaking rainfall associated with Hurricane Harvey. Additional information is available in Chapter 17: Complex Systems, Box 17.1.

In an attempt to recover from Hurricane Harvey and help prepare for future hurricanes, leaders in government, education, business, and nonprofit organizations gathered to identify unmet needs across all of the affected communities. For example, the Rebuild Texas Fund has a special focus on serving low-income communities and their most vulnerable members (<https://www.rebuildtx.org>). It was developed to support organizations that provide services in four focus areas: health and housing, schools and child care, workforce and transportation, and capital for rebuilding small businesses.



Figure 23.2: Texas Army National Guard assisting in flood rescues associated with Hurricane Harvey, August 27, 2017. Photo credit: Lt. Zachary West, Texas National Guard.

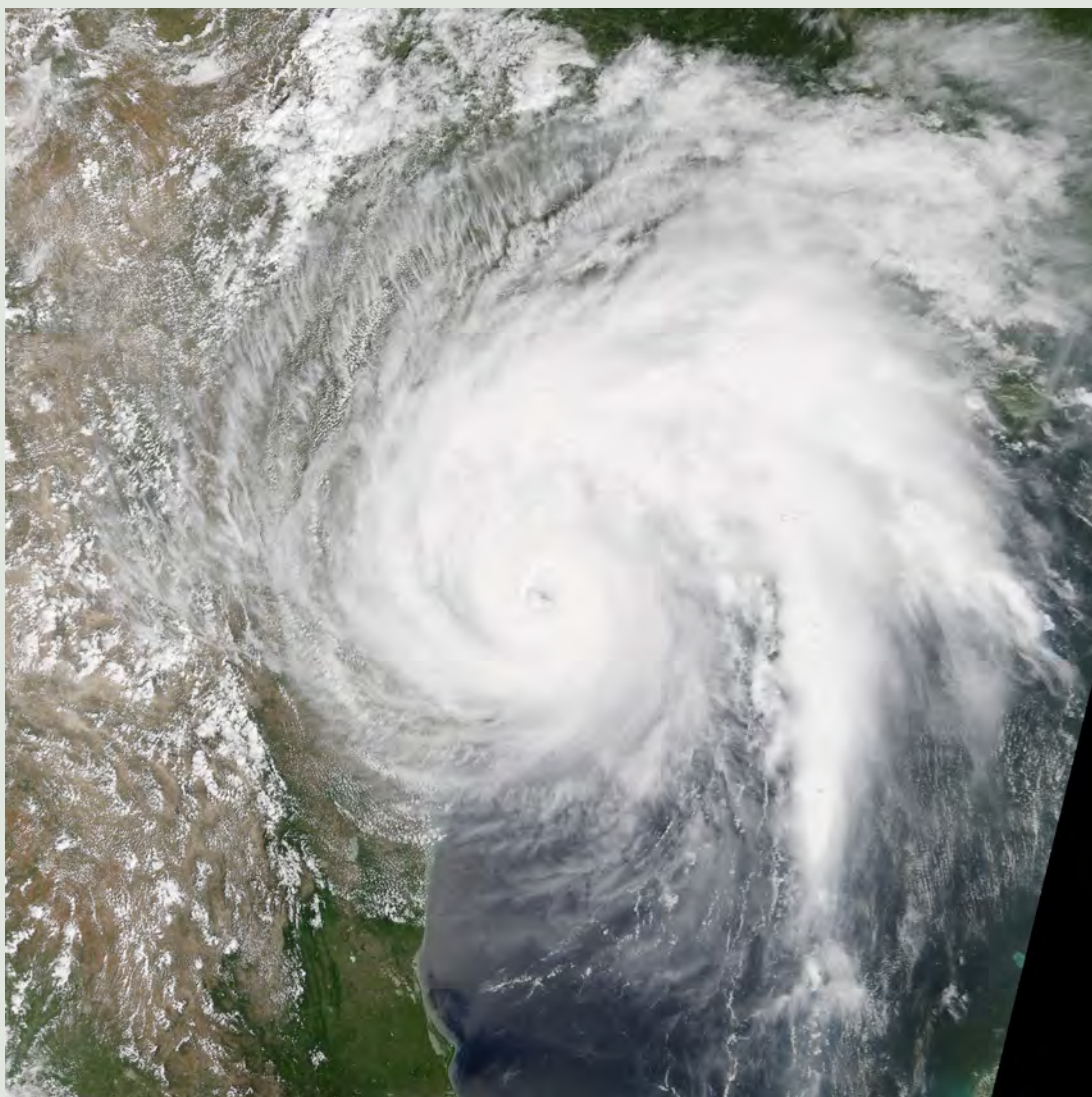
Box 23.1: Hurricane Harvey, *continued*

Figure 23.3: This visible satellite image shows Hurricane Harvey approaching the Texas coast on August 25, 2017. Image credit: NASA Earth Observatory.

Over the past 50 years, significant flooding and rainfall events followed drought in approximately one-third of the drought-affected periods in the region when compared against the early part of the 20th century.¹⁰ Understanding this rapid swing from extreme drought to flood is an important and ongoing area of research in the region. As major metropolitan areas in the

region continue their rapid population growth, overall exposure to extreme rainfall events will increase. Yet, even while record-breaking flooding events increased over the past 30 years, the Southern Great Plains experienced an overall decrease in flood frequency,¹¹ possibly related to the decrease in total precipitation over the same period.

The Southern Great Plains is a critical thoroughfare for rail and road freight, supports numerous ocean and river ports within its borders, and is a major energy producer and exporter.¹² Combined, the three-state region accounts for 25% of all U.S. energy production. The world's largest oil-storage tank facility is located in Cushing, Oklahoma, with 13% of total U.S. storage and a convergence of several major pipelines. More than 550,000 miles of roads connect rural and urban communities and serve as vital infrastructure supporting state and local economies.^{13,14,15} The vast and dispersed nature of the region's infrastructure makes investment in maintenance and rehabilitation of deficient and aging infrastructure difficult. Infrastructure is typically designed to withstand historical climate extremes and is exposed to the environment year-round. Therefore, as the intensity and frequency of climate-related extremes (such as heat, drought, flooding, and severe storms) increase, impacts to the region are usually adverse and costly. The Southern Great Plains ranks near the top of states with structurally deficient or functionally obsolete bridges, while other bridges are nearing the end of their design life.^{16,17,18} Road surface degradation in Texas urban centers is linked to an extra \$5.7 billion in vehicle operating costs annually (dollar year not reported).¹⁵ The region has tens of thousands of dams and levees; however, many are not subject to regular inspection and maintenance and have an average age exceeding 40 years.^{16,17,18} Most state and local budgets are unable to meet the funding needs for infrastructure improvements, particularly in rural towns where funding is largely derived from municipal revenue. In urban centers, population growth is anticipated to require expansion of transportation infrastructure and services and revisions to flood control structures and policies^{16,17,18} and result in increased water resource needs and a growth in building demand.^{19,20}

Understanding the potential for future changes in the frequency and severity of weather events and their impacts will ultimately determine the sustainability of economies, cultures, ecosystems, health, and life in the region. Over the past two decades, state and local governments have invested in the creation of weather monitoring networks ("Mesonets") that are designed to measure important weather and climate parameters (Figure 23.1).²¹ Mesonet stations are critical infrastructure required to establish the long-term climate record for the region. Mesonet observations have been especially critical for predicting and preparing for extreme weather events like droughts, floods, ice storms, and severe convective storms, as well as for developing value-added products. These data are used daily by decision-makers, public safety officials, educational institutions, the agricultural sector, and researchers, generating societal and economic benefits that greatly exceed the investments made in these systems.^{22,23}

Projections

Climate change is expected to lead to an increase in average temperatures as well as frequency, duration, and intensity of extreme heat events and a reduction in extreme cold events. Annual average temperatures in the Southern Great Plains are projected to increase by 3.6°–5.1°F by the mid-21st century and by 4.4°–8.4°F by the late 21st century, compared to the average for 1976–2005, and are dependent on future scenario, with higher levels of greenhouse gas emissions leading to greater and faster temperature increases. Extreme heat will become more common. Temperatures similar to the summer of 2011 will become increasingly likely to reoccur, particularly under higher scenarios. By late in the 21st century, if no reductions in emissions take place, the region is projected to experience an additional 30–60 days per year above 100°F than it does now (Figure 23.4).²⁴

Projected Increase in Number of Days Above 100°F

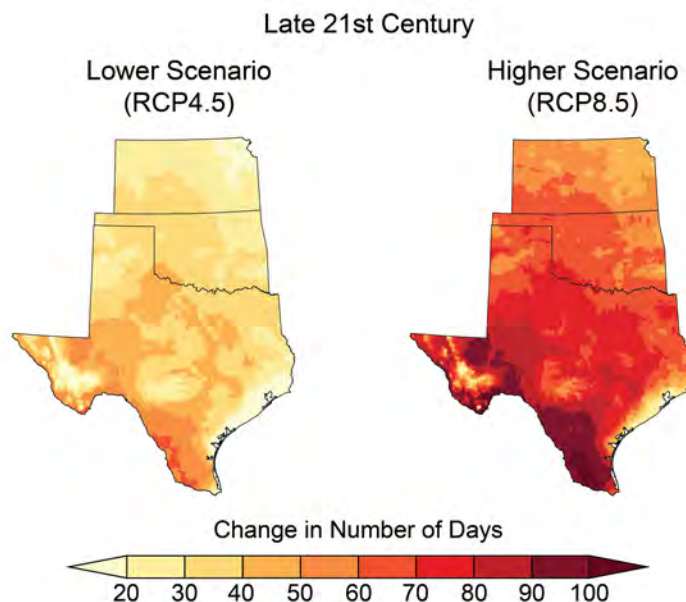


Figure 23.4: Under both lower- and higher-scenario climate change projections, the number of days exceeding 100°F is projected to increase markedly across the Southern Great Plains by the end of the century (2070–2099 as compared to 1976–2005). Sources: NOAA NCEI and CICS-NC.

The role of climate change in altering the frequency of the types of severe weather most typically associated with the Southern Great Plains, such as severe local storms, hailstorms, and tornadoes, remains difficult to quantify.^{1,2} Indirect approaches suggest a possible increase in the circumstances conducive to such severe weather,³ including an increase in the instances of larger hail sizes in the region by 2040,⁴ but changes are unlikely to be uniform across the region, and additional research is needed.

Along the Texas coastline, sea levels have risen 5–17 inches over the last 100 years, depending on local topography and subsidence (sinking of land).²⁵ Sea level rise along the western Gulf of Mexico during the remainder of the 21st century is likely to be greater than the projected global average of 1–4 feet or more.²⁶ Such a change, along with the related retreat of the Gulf coastline,²⁷ will exacerbate risks and impacts from storm surges.

Average annual precipitation projections suggest small changes in the region, with slightly wetter winters, particularly in the north of the region, and drier summers.¹ However, the frequency and intensity of heavy precipitation are anticipated to continue to increase, particularly under higher scenarios and later in the century.¹ The expected increase of precipitation intensity implies fewer soaking rains and more time to dry out between events, with an attendant increase in soil moisture stress. Studies that have attempted to simulate the consequences of future precipitation patterns consistently project less future soil moisture, with future conditions possibly drier than anything experienced by the region during at least the past 1,000 years.²⁸

While past hydrologic extremes have been driven largely by climate variability, climate change is likely to exacerbate aridity in the Southern Great Plains, largely associated with drying soils due to increased evapotranspiration caused by higher temperatures.^{1,29}

Key Message 1

Food, Energy, and Water Resources

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

Food, energy, and water systems are inseparable. Any change in demand for one will impact demand on the other two. The quality of life of the 34 million people residing in the Southern Great Plains is dependent upon the resources and natural systems for the sustainable provision of food, energy, and water. At least 60% of the region's population is clustered around urban centers, which are experiencing population growth that exceeds that of rural communities. The remaining population is spread across vast areas of rural land.^{14,30,31,32,33} As the population in the region grows, rapid urbanization and economic development opportunities will drive an increase in the demand for food, energy, and water. Water is used in every aspect of agricultural production and electricity generation. Energy is required to extract and deliver water of sufficient quality for diverse human and agricultural use, as well as healthy consumption and wastewater treatment. Both water and energy are required to irrigate and process agricultural products and livestock to feed the region's increasing population. The complex interdependencies at the food–energy–water nexus create enormous challenges.

When severe drought affected the Southern Great Plains in 2011, limited water availability constrained the operation of some power plants and other energy production activities. Contention for water developed between consumers associated with the food–energy–water nexus. The recent boom in domestic unconventional oil and gas development brought on by hydraulic fracturing and horizontal drilling represents another stressor to this nexus. This development has added complexity to the regional dialog about the relationship between food, energy, and water resources.

Superimposed on the existing complexities at the intersection of food, energy, and water is the specter of climate change. During 2010–2015, the multiyear regional drought severely affected both agricultural and aquatic ecosystems. One prominent impact was a reduction of irrigation water released for the Texas Rice Belt farmers on the Texas coastal plains, as well as a reduction in the amount of water available to meet instream flow needs in the Colorado River and freshwater inflow needs to Matagorda Bay. The Lower Colorado River Authority (LCRA), through its Water Management Plan (WMP), balances the needs of competing water demands in the Lower Colorado River Basin of Texas. Depending upon the amount of water stored in lakes, the WMP requires that LCRA reduce or cut off interruptible stored water for most downstream agriculture so firm water supplies are available to meet the basic needs of cities, businesses, and industries during drought.

In one year, planted acres of rice in Matagorda County, Texas, dropped from 22,000 acres to 2,100 acres.³⁴ The ripple effect on the local economy was severe, with a 70% decline in sales of farm implements and machinery. Some family-owned establishments that had survived for decades closed permanently.³⁵ Irrigation strategies shifted from river-based to pumping



Figure 23.5: The photo shows the drought impact on a stock pond near Kurten, Texas, in 2011. Photo credit: John Nielson-Gammon.

water from the Gulf Coast Aquifer, and dozens of new wells were drilled. Drilling water wells then resulted in declining groundwater levels, adding stress to water levels that had historically been falling in the region.³⁶ Some farmers attempted to adapt by making the difficult transition to other crops such as corn. However, when flooding rains inundated the region in 2016, 15% of the corn crop was swept away in flood waters.³⁷ Thus the 2010–2015 drought simultaneously affected agriculture, energy, recreation, and economic activity, eventually leading to increased groundwater development and potential future overexploitation. Projected increases in drought duration and severity

imply even more pervasive direct and indirect effects. These impacts might have been even more severe had it not been for adaptation actions taken by the City of Austin, including implementation of drought contingency plans and water-use cutbacks in coordination with the City Council and community.

Climate change has significant negative impacts on agriculture in the United States, causing substantial economic costs (Ch. 10: Ag & Rural).^{38,39} The effects of drought and other occurrences of extreme weather outside the Southern Great Plains also affect the food–energy–water nexus in the region. The neighboring Southwest region is especially vulnerable to climate change due to its rapidly increasing population, changing land use and land cover, limited water supplies, and long-term drought (Ch. 25: Southwest).⁴⁰ States in the Southern Great Plains import over 20% of their food-related items from Arizona, and El Paso, Texas, receives 25% percent of its consumable foods (mostly vegetables) and 18% of its animal feed supplies from Arizona.⁴¹ In addition, relationships across the border of the Southern Great Plains with Mexico will be critical to a better understanding of the food–energy–water nexus (see Case Study “Rio Grande Valley and Transboundary Issues”) (see also Ch. 16: International, KM 4).

Case Study: Rio Grande Valley and Transboundary Issues

In the U.S.–Mexico transboundary region of the Southern Great Plains, no hydrologic resource is more critical than the Rio Grande and its attendant tributaries. Partnered, binational management of the basin’s water supply is essential to supporting the agricultural, industrial, and community infrastructure in place along the Rio Grande valley. Proactive and collaborative water management strategies allow for effective flood control, mitigation of drought impacts, and maximization of water quality, among other benefits.⁴²

The Rio Grande is highly sensitive to variations and changes in the climate of the Southern Great Plains, where changes can have marked impacts on the valley’s extensive agricultural productivity.^{43,44} Increasing regional temperatures,⁴⁵ consistent with global trends, will enhance the severity of drought impacts via the acceleration of surface water loss driven by evaporation, particularly in large Rio Grande reservoirs such as Lake Amistad. Changes in regional precipitation patterns, including observed increases in extreme rainfall events as part of a regional “dipole” dry-wet-dry-again pattern,¹⁰ will affect both drought and flood occurrence and intensity along the Rio Grande channel. Other climate-driven impacts, such as changes in wildfire frequency⁴⁶ and increased vulnerability to heat events,⁴⁰ will further challenge the preparedness and resilience of communities on both sides of the border.

A growing number of adaptation strategies⁴⁷ and an increasing provision of regional climate services in the Southern Great Plains⁴⁸ bode well for an improved future ability to effectively manage the Rio Grande’s transboundary water interests. This is particularly true in the context of early warning decision support systems. Frequently, extreme weather and climate events, such as the 2011–2012 La Niña and 2015–2016 El Niño episodes, serve as catalyzing opportunities to develop new and refine existing information delivery pathways from climate services providers to stakeholder audiences. One recent application in the Rio Grande transboundary region is bilingual seasonal climate outlooks and impact assessments,⁴⁹ which are utilized by stakeholders to strengthen regional drought and wildfire outlooks⁴⁶ and which augment other ongoing efforts to strengthen bilingual climate services delivery.⁵⁰



The Rio Grande Gorge near Taos, New Mexico. Photo credit: © flickr.com/josephmccowie.

Case Study: Rio Grande Valley and Transboundary Issues, *continued*

Highlighting Seasonal-Scale Extreme Events in a Transboundary Setting

AT A GLANCE

- 1 New Mexico, North Texas**
Severe to extreme drought conditions developed over the past month, and drought is likely to persist in these regions through May.
- 2 Rio Grande/Bravo Region**
High fuel loads from warm, dry conditions, coupled with the increasing frequency of wind events common during early spring in the region, will increase the risk of intense, fast-spreading fires through April.
- 3 New Mexico, North Texas**
Precipitation was 0-25% of average from November – January.



UN VISTAZO

- 1 Nuevo México, Norte de Texas**
Condiciones severas a extremas de sequía se desarrollaron durante el mes pasado, y es probable que la sequía persista en estas regiones hasta mayo.
- 2 Región de Rio Grande / Bravo**
Las altas cargas de combustible provenientes de las condiciones cálidas y secas, junto con la frecuencia cada vez mayor de los eventos de viento comunes a comienzos de la primavera en la región, aumentarán el riesgo de incendios intensos y de rápida propagación hasta abril.
- 3 Nuevo México, Norte de Texas**
La precipitación fue 0-25 % del promedio de noviembre a enero.



Figure 23.6: Shown here are the English- and Spanish-language versions of the February 2018 Climate Assessment for the Southwest Rio Grande-Bravo Climate Impacts and Outlook “At a Glance” summary. Source: Garfin et al. 2018.^{44,51}

The 2017 Texas State Water Plan⁵² indicates that the growing Texas population will result in a 17% increase in water demand in the state over the next 50 years. This increase is projected to be primarily associated with municipal use, manufacturing, and power generation, owing to the projections of population increase in the region. Likewise, the Oklahoma Water Plan indicates that water use projections in Oklahoma are expected to increase by 21% for municipal use, 22% for agricultural use, and 63% for energy use.⁵³ The Kansas Water Plan's preliminary assessment of projected water demand in Kansas also shows an increase of 20%, but with the expected variability depending upon rural versus urban areas.⁵⁴ Throughout much of western Kansas, western Oklahoma, and the Texas Panhandle, groundwater from the Ogallala Aquifer is the dominant water source,^{17,55} benefitting the agricultural sector in particular. This resource is known to be shrinking faster than it is replenishing, and some portions are likely to become an insufficient source or become completely depleted within the next 25 years, particularly at its southernmost extent.¹⁷ Drought more

persistent than that experienced in the region's recent history would trigger large social and economic consequences, including shifting agriculture, migration, rising commodity prices, and rising utility costs.²⁰

The importance of groundwater as a resource will increase under a changing climate as the intensification of hydrologic extremes decreases the reliability of precipitation, soil moisture, and surface water, and as surface water supplies are becoming increasingly over-allocated.^{56,57,58}

Research into the food–energy–water nexus is in its early stages and historically tends to examine only one or two components.^{59,60,61,62,63,64,65} It is clear that tradeoffs and cascading complexities exist between sectors, and changes in one sector are likely to propagate through the entire system (Ch. 17: Complex Systems). There are significant gaps in the scientific understanding regarding the role that climate change will play as a disruptive force and a threat to food, energy, and water security.^{60,63,66,67,68}



Wind turbines near Kansas farmland. Photo credit: © flickr.com/Kansas State Research and Extension.

Case Study: The Edwards Aquifer

The Edwards Aquifer is a “karst” aquifer, composed of limestone and characterized by solution features such as large pores, caves, sinkholes, and conduits that channel groundwater flow. The Edwards provides groundwater to the central Texas region. It serves more than two million people, including the cities of San Antonio, San Marcos, and Austin, which are three of the fastest-growing cities in the country.⁶⁹ The aquifer is a source of water for drinking, industry, agriculture, livestock, and recreation. In particular, San Antonio relies nearly entirely on the Edwards for its drinking water. The aquifer is also a habitat for a number of endemic and endangered species. As a shallow karst aquifer, the Edwards is especially sensitive to climate change. Its shallow depth and karst features allow for rapid infiltration and recharge during wet periods, and discharge is similarly responsive, making the Edwards vulnerable to climate extremes of droughts and floods. This high susceptibility and exposure to climate change is a major challenge for managing the Edwards Aquifer as a resource.⁷⁰ The probable impacts of climate change for the Edwards Aquifer include a decrease of water supply during droughts, a degradation of habitat for species of concern, economic effects, and the interconnectivity of these impacts. These climate change impacts will be exacerbated in central Texas’s rapidly urbanizing regions, as increasing impervious cover will affect water quality and rates of runoff and recharge.

Water availability and demand: The population of Texas is projected to grow by more than 70% between 2020 and 2070, with the majority of the increase projected to occur in urban centers.⁵² Increased demand for water will come from municipal, power generation, agriculture, manufacturing, and livestock uses.⁵² Over this same period, water availability in the U.S. Southwest is projected to decrease due to a shift to a more drought-prone climate state.^{28,71} History shows that increases in population and pumpage from the Edwards led to unsustainable use of water from the aquifer during the drought of the 1950s.⁷² The lessons learned from the 1950s drought and the more intense 2011 drought provide a well-suited application for models of how the aquifer and associated ecosystems will respond to further climate change.⁷³

Cross Section of Edwards Aquifer

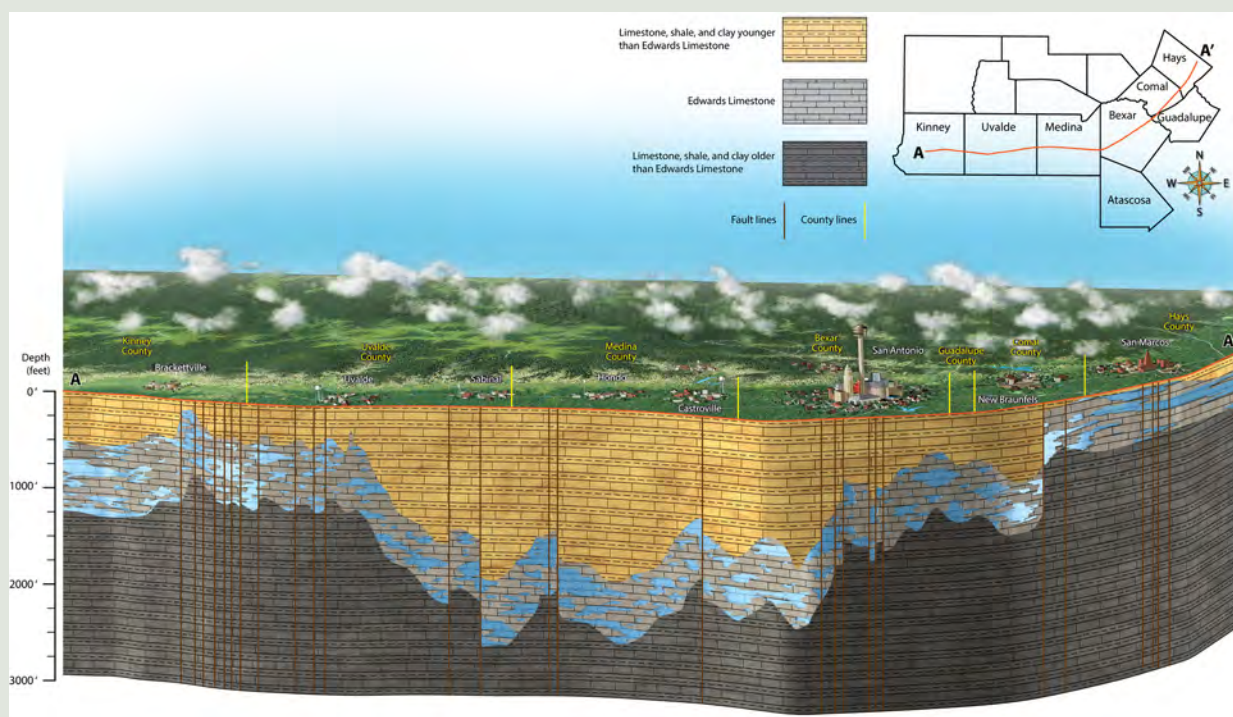


Figure 23.7: Key characteristics of the Edwards Aquifer, such as relative shallowness and karst features, make it vulnerable to the impacts of both climate variability and climate change. Its importance as a major supplier of groundwater in central Texas makes these vulnerabilities even more pronounced. Source: Edwards Aquifer Authority.⁷⁹ Used with permission.

Case Study: The Edwards Aquifer, *continued*

Habitat: Plants and animals are sensitive to a variety of changes related to the Edwards Aquifer groundwater system, including changes in habitat, water levels, spring flows, and water quality. An example of the last is an analysis of dissolved oxygen concentrations (DO) in water in Barton Springs, a major point of discharge from the Edwards Aquifer. Most notable are water quality effects on the Barton Springs salamander (*Eurycea sosorum*), a federally listed endangered species native to these springs. An analysis of DO, discharge, and temperature measurements at the springs indicates that low DO episodes that correspond to salamander mortality could result from 1) lower discharge from the springs resulting from increased water withdrawals or decreased recharge as a result of drought, and/or 2) increased water temperature as a result of climate change.⁷⁴ A key challenge is understanding and modeling the extent to which endangered and native species can be protected in their habitats associated with the aquifer.^{73,75,76}

Impacts: Dramatic drawdowns of groundwater levels by human activity combined with climate change in many regions illustrate the challenges of the nonrenewable nature of groundwater and the multiple dependencies of some ecosystems and agricultural systems on groundwater.⁷⁷ Multiple, integrated solutions will be needed to address the impacts on the Edwards Aquifer. These will necessarily involve ways to increase supply through technological approaches, such as desalination of brackish groundwater and aquifer storage and recovery; ways to decrease demand, such as conservation and regulation; and ways to reduce the impact of urbanization through sustainable design. For example, The Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan⁷⁸ balances water pumping and use of the aquifer with protection of eight federally listed threatened and endangered species that depend on San Marcos Springs and Comal Springs, two of the largest springs in the southwestern United States. The plan incorporates a number of innovative water supply strategies including Aquifer Storage and Recovery and advanced water conservation, along with market-based solutions for voluntary suspension of groundwater pumping rights during drought periods.

Key Message 2

Infrastructure

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

Climate change is anticipated to lead to higher average temperatures year-round and an increase in the frequency of very hot days (days with maximum temperatures above

100°F), with the number of such days possibly doubling by mid-21st century (Figure 23.4).⁸⁰ An increase in temperatures is *virtually certain* for the Southern Great Plains. Longer, hotter summers will place strain on cooling systems and energy utilities, road surfaces, and water resources, particularly during drought, although warmer winters are likely to reduce heating demands and winter road maintenance costs. The rate of temperature rise will be especially large within urban centers due to possible intensification of the urban heat island (UHI) effect, although the degree of heating will likely vary by city, and it is difficult to obtain precise quantitative estimates. Warmer temperatures will likely lead to an increase in evaporation and therefore an increase in moisture in the air^{81,82} and an increase in heat stress, especially during the summertime.⁸³ During excessive heat in July 2011, downtown

Dallas experienced late-evening temperatures 6.1°F higher than rural Kaufman, Texas, 36 miles away.⁸⁴ Population growth, increased urban density, and expansion will intensify the UHI effect for many Southern Great Plains cities, necessitating more energy use for cooling. This strains energy utilities and can further enhance the UHI effect.⁸⁵ If prolonged power failure occurs during high heat conditions, the impact to human health and comfort is projected to be notably more detrimental in a warmer climate.⁸⁶

Increased aridity (or dryness) is also projected for the Southern Great Plains with climate change, due to enhanced evapotranspiration and depleted soil moisture associated with increased temperatures.^{1,29} In the past, drought conditions have decreased surface water availability (such as from reservoirs), leading to an increase in the use of groundwater. In some cases, new pipelines were needed and water had to be imported.²⁰ Compounding infrastructure challenges for the region include aging and over-capacity water pipelines.⁵³ The Texas Water Development Board⁸⁷ projected that by 2060, municipal water use will increase to 41% of available supply (versus 9% in 2010). Therefore, a record drought scenario occurring in 2060 would result in as much as half of the state's population facing a water supply shortage. Additionally, water infrastructure can be damaged by drought. During summer 2011, water main breaks were common, with 200 breaks in Fort Worth, Texas, in one month and over 1,000 in one month in Houston, Texas,²⁰ associated with shrinkage of clay soil, a common soil type throughout the Southern Great Plains. Soil shrinkage can damage both surface and subsurface infrastructure, including roads, water and sewer lines, and building foundations. Periods of abundant precipitation followed by drought and high temperatures are also linked to increased wildfire activity in the region.⁸⁸ Texas experienced several major

wildfire outbreaks during the drought of 2011, including the Bastrop Fire that destroyed more than 1,500 homes. More recently in 2016 and 2017, fires in Kansas and Oklahoma have exceeded 400,000 acres and were among the largest in the region's history. These events killed thousands of cattle, contributed to several human fatalities, and damaged, displaced, or isolated rural communities.⁸⁹ Model simulations indicate that wildfire risk will increase throughout the region as temperatures rise, particularly in the summer, and the duration of the fire season increases.⁹⁰

Following the abrupt end to the persistent drought in 2015, the region suffered extensive damage associated with river and flash flooding.^{10,91,92} Precipitation totals for a 120-day period during the spring of 2015 in south-central Oklahoma were above 40 inches, approximately the average annual amount in many locations,^{93,94} largely associated with multiple episodes of very heavy rain. Numerous state and U.S highways experienced regional detours or closures.⁹⁴ A rockslide on Interstate Highway 35 closed portions of the road for several weeks.^{94,95} Flooding in Oklahoma and Texas caused an estimated \$2.6 billion in damage in 2015,⁹⁵ with \$1 million in emergency relief funds provided by the U.S. Department of Transportation's Federal Highway Administration to assist in the repair of damaged roads.⁹⁶ The increasing frequency of extreme precipitation that is projected by climate models is anticipated to contribute to further vulnerability of existing highway infrastructure, although the magnitude and timing of projected precipitation extremes remain uncertain.¹

Changing precipitation frequency and increases in the magnitude and frequency of heavy precipitation will place more stress on existing water resource infrastructure. The region has a large number of older dams and levees, many of which have received poor grades from

the American Society of Civil Engineers.^{16,17,18} Between 1982 and 2012, 82 dams failed in Texas, and during 2015 the high-hazard Lewisville Dam was of concern due to observed seepage.^{18,97} As climate conditions continue to change, rare events such as 100-year floods (those that currently have a 1% chance of occurring in any given year) are likely to become more common.^{1,29} Future extremes may exacerbate flooding and wear and tear on existing flood control infrastructure and will necessitate revisions to design standards for flood infrastructure and a reevaluation of floodplains. Floodplain management and mitigation of flooding are currently left largely to local governments and cities and are thus reliant on local funding and resources for successful implementation.^{16,17,18} While there are clear implications of more variable and extreme precipitation on infrastructure, the precise links between specific events and their resulting damage are uncertain as most infrastructure is exposed to both climatic and non-climatic stressors whose effects are difficult to separate without a high degree of monitoring.

As the energy industry undergoes, to some extent, a reinvention, it is taking climate and extreme weather events into consideration in design, operations, and reliability. An Edison Electric Institute (2008) study estimated that by 2030, the U.S. electric utility industry will need to make a total infrastructure investment of between \$1.5 trillion and \$2.0 trillion, of which transmission and distribution investment is expected to account for about \$900 billion.⁹⁸ These investments increasingly include renewable energy and distributed generation, smart grid technologies, and storage. From 2008 to 2013, the amount of electricity generated from wind has more than tripled and the amount from solar has increased more than tenfold.⁹⁹ These enhancements would need to be reliable (able to operate within limits so that

instability, uncontrolled events, or cascading failures do not result if there is a disturbance), resilient (able to adapt to changing conditions and withstand and rapidly recover from disruptions), safe, flexible, and affordable.

Coastal regions are among the most vulnerable to climate change due to their direct exposure to rising sea levels and damaging storm surge. Global mean sea level is very likely to rise by 1–4 feet (0.3–1.3 m) by 2100 relative to 2000 levels. Under certain future conditions, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed (Ch. 2: Climate, KM 4). Since the early 20th century, areas of the Texas coast have experienced sea level rise (SLR) higher than the global average, associated with extraction of both fossil fuels and groundwater.²⁵ Within Texas alone, 1,000 square miles of land is within 5 feet of the high tide line, including \$9.6 billion in current assessed property value and homes to about 45,000 people. Sensitive assets include 1,600 miles of roadway, several hospitals and schools, 4 power plants, and 254 EPA-listed contamination sites (hazardous waste and sewage).¹⁰⁰ Up to \$20.9 billion in coastal property is projected to be flooded at high tide by 2030, and by 2050, property values below the high-water mark are projected to be in excess of \$30 billion, assuming current trends of greenhouse gas emissions.¹⁰¹ The coastline in the vicinity of Galveston and Texas City is also a critical oil refining and transport hub. SLR will affect numerous coastal assets, including residential communities, roads, waterways, and energy generation facilities, and move the risk of damaging storm surge well inland of present areas of impact. With 2 feet of SLR, cities such as Galveston and Corpus Christi will be exposed to more frequent flooding.^{100,102,103,104} Disruption to coastal oil-refining facilities can cause cascading failures throughout the region, including fuel shortages and higher

prices. Saltwater intrusion of aquifers has been observed in the Gulf Coast Aquifer, the second most utilized aquifer in Texas, which supports 8 million people. Although this was in part associated with heavy pumping,¹⁰⁵ the Gulf Coast Aquifer remains vulnerable to further saltwater intrusion resulting from SLR and storm surge exacerbated by climate change.¹⁰⁶

Due to the historical frequency of drought, water conservation activities are already recognized as important and encouraged in many municipalities. Common strategies include rainwater harvesting, encouraging improved residential water-use efficiency, water audits, and restricted water use in times of drought.²⁰ Other proactive measures currently in place in some communities aim to mitigate longer-term risks and involve wastewater treatment and reuse, aquifer storage and recovery, and desalination (see Case Study “Meeting Current and Future Water Needs in El Paso, Texas”).²⁰

Climate change is likely to require modification and updating of design standards in order to accommodate changes in risk that cannot be accounted for based on history. For example, in transportation design, these modifications might include changing the minimum and maximum temperature rating for binders used in asphalt roads to improve durability; structural modifications to bridges to meet the demands of higher summer temperatures; updating the data used for calculating flooding of dams and neighborhoods; restricting rail speeds during hot temperatures; and shifting timing of maintenance activities. Many technological solutions exist or are in development to build resilience to these climate-related challenges. However, the aforementioned stressors and budgetary challenges will continue to present notable challenges to adaptive capacity in the Southern Great Plains (Ch. 12: Transportation).

Many studies have documented economic impacts of climate change on different sectors in the United States).^{111,112,113,114,115} For example, predictive analyses estimate that climate change and coastal development will cause hurricane damage to increase faster than the U.S. economy is expected to grow. The number of people expected to face substantial damage will, on average, increase more than eightfold over the next 60 years.¹¹⁶ Although economic analyses for specific regions, sectors, and states in the Southern Great Plains are currently limited, active ongoing research is beginning to produce critical metrics regarding the socioeconomic impacts of climate change at regional scales.¹¹⁷

The role of economics is increasingly recognized as being critical for advancing the resilience of households, businesses, and local governments, and also for the broader economic adaptation of entire regions. Establishing economic resilience in a local business or a regional economy requires the ability to anticipate risk, evaluate how that risk can impact key economic assets, and build a responsive adaptive capacity. At the regional or community level, economic development practitioners can build capacity for economic resilience.

Case Study: Meeting Current and Future Water Needs in El Paso, Texas

El Paso, Texas, is vulnerable to drought, being situated in the Chihuahuan Desert and with a growing population and limited water resources derived largely from the Rio Grande and regional aquifers. Average annual rainfall is only around 9 inches. The city continues to be a part of the Rockefeller Foundation's 100 Resilient Cities initiative. Prior to, and as part of, El Paso's ongoing climate adaptation planning, the city's water utility program implemented programs on water conservation, reclamation, and supply diversification. In 2007, the city completed construction of the 27.5 million-gallon-per-day Kay Bailey Hutchison Desalination Plant. The desalination is applied to previously unusable brackish waters in the Hueco Bolson Aquifer. Conversion of this brackish water to freshwater increased El Paso's water utilities' production by 25%.¹⁰⁷ The plant is designed to run at capacity only when needed, such as in times of drought. While desalination is expensive due to use of energy-intensive reverse osmosis, the plant was found to be more cost effective in the long term compared with importing water from remote sources. A climate change analysis of the future viability of this infrastructure suggested that it could meet the needs of the city through the next 50 years.¹⁰⁸ Across Texas, brackish water is abundant, estimated at 2.7 billion acre-feet, and an expansion of desalination is recommended in the state's 2017 Water Plan.¹⁰⁹ There are currently 44 public water supply desalination plants in Texas.

Texas Desalination Plants

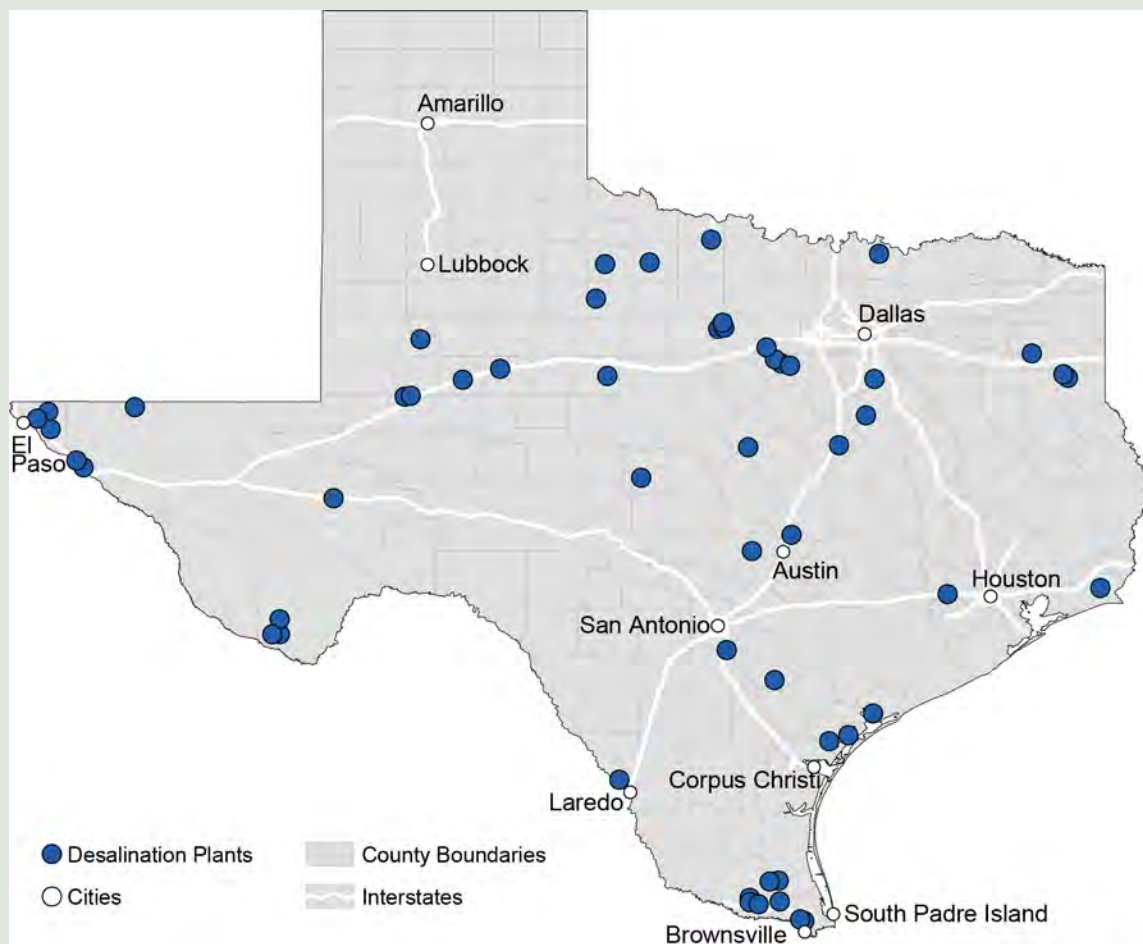


Figure 23.8: Desalination activities in Texas are an important contributor to the state's efforts to meet current and projected water needs for communities, industry, and agriculture. Source: adapted from Texas Water Development Board 2017.¹¹⁰

Key Message 3

Ecosystems and Ecosystem Services

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

The Southern Great Plains encompasses diverse ecoregions (areas where ecosystems are generally similar) stretching from the High Plains to the Edwards Plateau and from the Tamaulipan Brushlands to the Gulf Coast Prairie.¹¹⁸ The region is prone to periods of drought punctuated by heavy rainfall events, with evidence that these events are occurring more frequently.¹⁰ These precipitation patterns influence water availability and aquatic habitats such as lakes, rivers, springs, and streams. Freshwater inflows from rivers flowing to coastal estuaries provide important nutrients and sediments while moderating salinities to create and maintain productive estuarine ecosystems.

Species Distribution and Habitats

Climate plays a key role in the distribution of species (Ch. 7: Ecosystems). Species' response to climate change is complex and variable.¹¹⁹ As temperatures increase, the geographic distribution of some species tends to shift to areas with temperature ranges where a given species can survive. A notable species of concern in the region is the lesser prairie-chicken, which was listed as threatened under the U.S. Endangered Species Act in May 2014. Currently, the lesser prairie-chicken habitats

include Kansas, Texas, and Oklahoma (as well as Colorado and New Mexico) with 70% of the population in Kansas.¹²⁰ At this time, it is not clear whether climate change will influence the lesser prairie-chicken in positive or negative ways.^{121,122} Rising temperatures are also causing changes to growing seasons and migration patterns of birds and butterflies.¹²³ In Texas, white-wing doves, originally confined to the Lower Rio Grande valley, have been expanding northward¹²⁴ and are now common across Oklahoma. Other factors such as habitat loss also influence species distributions, making it difficult to pinpoint a single cause for these distribution changes.

While it is unclear how climate change will affect species directly, the effects of increased aridity will likely have negative impacts. In addition, ecosystem services—the materials and processes that ecosystems produce that benefit people—will also be affected.¹²³ In general, drought forces wildlife to travel farther to locate food, water, and shelter, which can deplete body condition going into winter or spring migration, when food sources are typically scarcer, making them more vulnerable to other stresses. The highly endangered Houston toad was negatively impacted during the 2011 drought and devastating wildfire in Bastrop County, Texas. Whooping crane numbers, which depend on sufficient freshwater inflows for a reliable food source (primarily blue crabs), were also reduced. In addition, a lack of freshwater can force whooping cranes to fly to uplands to drink, using more energy and exposing birds to more threats from predators and other mortality factors.

Aridification exacerbates stress in highly isolated habitats and fragmented lands, diminishing the ability for species to persist if they cannot move to better conditions. Migratory birds are better able to move to areas with better habitat conditions but could be in a weakened condition to do

so. Migratory waterfowl can also be negatively impacted by reductions in wetland habitat areas due to aridification. Loss of irrigated rice fields in Texas contributed to significant declines in wintering waterfowl along the Gulf Coast. The most significant decline was documented for snow geese, with a 71% decline for 2011–2014 as compared to the long-term average.¹²⁵ Playa lakes in the High Plains serve as important habitat for migrating waterfowl, but during the drought these wetlands were virtually nonexistent.

Plant community changes are also occurring, possibly due to climate change and other factors, and these changes in turn affect fish and wildlife. In the Southern Great Plains region, winters are warmer and spring is arriving earlier. Along the Texas coast, black mangroves, which are sensitive to cold, are expanding northward along the coast, and red mangroves, formerly not found in Texas, are now appearing there.¹²⁶ Warmer winters with fewer freezes are also conducive to pests and diseases. Woody shrubs invading prairie grasslands are favored by increases in concentrations of carbon dioxide (CO₂), changes in soil moisture cycles, fire suppression activities, and soil disturbances.¹²⁵ The 2011 drought produced a direct and indirect tree mortality rate of over 6%—many times the normal rate.¹²⁷

Aquatic Ecosystems

Climate change impacts to aquatic ecosystems include higher water temperatures in lakes, wetlands, rivers, and estuaries that can result in lower dissolved oxygen, leading to more fish kills. Impacts to reservoirs include fluctuating lake levels, loss of habitat, loss of recreational access, increase in harmful algal blooms, and disconnectedness from upstream and downstream riverine habitats.¹²⁸ Localized declines in fish populations have been documented in rivers due to lack of water or water confined to increasingly narrow pools; in some cases, these declines prompted biologists to capture and relocate some

endangered species to fish hatcheries.¹²⁹ Aridification (a gradual change to a drier climate) can have a number of negative impacts on freshwater mussel populations, including increased predation pressures, hypoxia (low oxygen conditions), increasing water temperature, and, ultimately, anoxia (no dissolved oxygen in water) or emersion (stranding the organism out of water and exposing it to air).

Coastal Areas, Bays, and Estuaries

The Texas coast, with 6.5 million people contributing over \$37 billion to the region's economy, relies on its natural features, bays, and estuaries that serve as storm barriers to protect coastal infrastructure, and on its climate amenities to spur ecosystem services, such as fishing, ecotourism, and the ocean economy. These coastal ecosystems provide protection not only for people but also for 25% of the Nation's refining capacity, four crucial ports, much of the strategic petroleum reserves, and strategic military deployment and distribution installations. This protection was clearly on display with the recent impacts of Hurricane Harvey, where it has been estimated that natural coastal habitats protected about \$2.4 billion worth of property in Texas and thousands of lives, with the suggestion that these habitats are potentially our first lines of defense.¹³⁰

A rising sea level impacts more than 74% of Gulf-facing beaches in the upper Texas coast. The average rate of beach erosion is almost 10 feet per year.¹³¹ Sea level rise means more frequent and longer-lasting flooding of marshes that eventually could be permanently flooded, becoming open water.^{126,132} Higher tides and storm surges cause inundation of freshwater areas and beach erosion, leading to a potential decrease or loss of barrier islands and coastal habitats, including nesting habitats and submerged habitat such as seagrass beds affected by changes in water quality and changing water depths. A significant percentage of fishery species in the Gulf of Mexico are

dependent upon estuaries for some portion of their life cycle.¹³³

The warming of bay waters on the Texas coast has been documented for at least 35 years. This mostly reflects warmer winters, not warmer summers. The increase in water temperature directly affects water quality, leading to the higher potential for low levels of dissolved oxygen, or hypoxia. Hypoxic events and harmful algal blooms have caused fish kills, leading to lower productivity and diversity of estuarine ecosystems.¹²⁶

Freshwater inflows are critical to both aquatic ecosystems and wetlands in the Southern Great Plains. Both surface and groundwater depletion have led to dramatic changes of the aquatic and wetland communities in Kansas¹³⁴ that not only impact inland species but have a dramatic effect on coastal species relying on the freshwater inflow to ensure the integrity of the coastal ecosystem. Whooping crane and many other migratory species flying through this region during both spring and fall are impacted.¹³⁵ Climate change and human use have impacted these aquatic systems and wetlands and, ultimately, the vital flow of freshwater to the coastal marshes and estuaries.

Changes to freshwater inflows to estuaries lead to changes in salinity and inflows of nutrients and sediment, resulting in impacts to oysters and other sensitive estuarine species. In addition, harmful algal blooms have become more frequent, more intense, and more widespread.¹²³ Reduced freshwater inflows during 2011 led to record high salinities in Texas estuaries that contributed to a coast-wide “red tide” harmful algal bloom event. Red tides, a type of harmful algal bloom, most commonly occur during drought years, as the organism that causes red tide does not tolerate low salinity. Red tide blooms cause fish kills and contaminate oysters. In addition, oysters and other shellfish can accumulate red tide toxins in their tissues. People who eat oysters or other shellfish containing red tide toxins become seriously ill with neurotoxic shellfish poisoning. Once a red tide appears to be over, toxins can remain in the oysters for weeks to months. The 2011 bloom started in September and lasted into 2012. Fish mortality was estimated at 4.4 million. The commercial oyster season was closed and disaster declarations issued. The total economic loss was estimated at \$7.5 million (dollar year not reported).¹³⁶

Climate Winners and Losers (Gray Snapper and Southern Flounder)

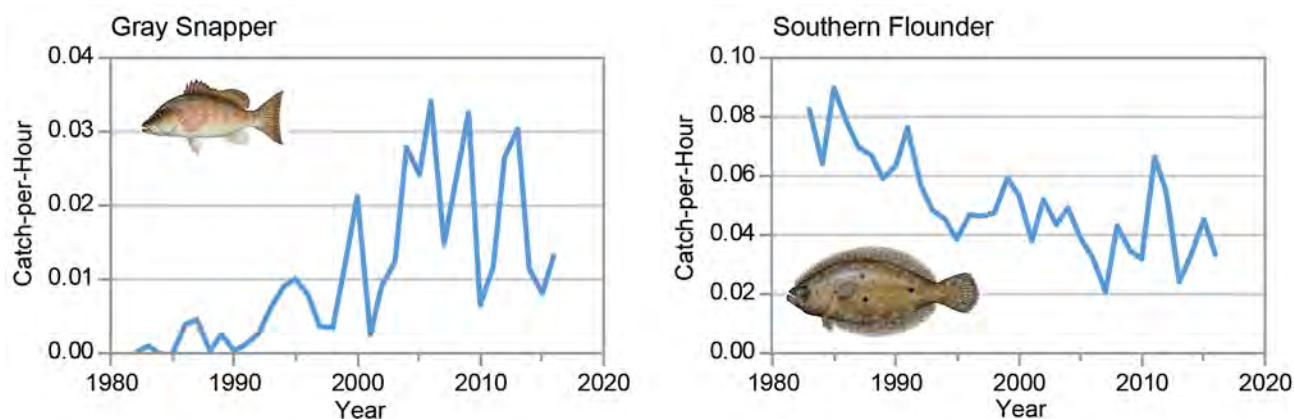


Figure 23.9: The graphs show trends in annual abundance of (left) gray snapper and (right) southern flounder as the number of fish caught per hour along the Gulf Coast of Texas between 1982 (snapper)/1983 (flounder) and 2016. As water temperatures increase along the Texas Gulf Coast, gray snapper are expanding northward along the Texas coast, while southern flounder, a popular sport fish, are becoming less abundant, impacting the recreational and commercial fishing industries. Source: Texas Parks and Wildlife Department.

Gray snapper have been ranging farther north since the 1990s; once found only in the lower Laguna Madre and off the extreme southern shore of Texas, they are now migrating northward along the upper Texas Coast. Conversely, flounder abundance has been declining due to the warmer winters,^{137,138} since sex ratios (the number of males versus females) are influenced by temperature during flounder development and increases in temperature produce increasingly male-dominated sex ratios in southern flounder from Texas (See Figure 23.9).

Existing Options for Managing Risk

The National Fish, Wildlife, and Plants Climate Adaptation Strategy¹²³ was developed to provide natural resource managers and decision-makers the strategies and tools to address climate change impacts. The Strategy offers a guide for actions that can be taken in spite of remaining uncertainties over how climate change will impact living resources.

The Texas Edwards Aquifer Recovery Implementation Program Habitat Conservation Plan⁷⁸ balances water pumping and use of the aquifer with protection of eight federally listed threatened and endangered species that depend on San Marcos Springs and Comal Springs, two of the largest springs in the southwestern United States. These springs are the headwaters of the San Marcos and Comal Rivers and provide important water flow, especially during drought, to the Guadalupe River and Estuary.

Environmental flows—instream flows and freshwater inflows to bays and estuaries—are critical for sustaining aquatic ecosystems. In 2007, the Texas Legislature passed Senate Bill 3, which established a comprehensive, statewide process to protect environmental flows.¹³⁶ The process relies upon input from local stakeholder groups, composed of balanced interests ranging from agricultural water users to commercial anglers. The Texas Commission on Environmental Quality

has adopted environmental flow standards intended to protect flow regimes that will help ensure healthy rivers, streams, and estuaries for Texas. The focus now is on adaptive management to refine standards, address research needs, and identify voluntary strategies to meet environmental flow standards.

The Texas Coastal Resiliency Master Plan¹³⁹

promotes coastal resilience, defined as the ability of coastal resources and coastal infrastructure to withstand natural or human-induced disturbances and quickly rebound from coastal hazards. This definition encompasses the two dimensions of resilience: 1) taking actions to eliminate or reduce significant adverse impacts from natural and human-induced disturbances, and 2) responding effectively in instances when such adverse impacts cannot be avoided. To keep pace with the dynamic Texas coastline, the Plan will be updated regularly to allow the state to continually assess changing coastal conditions and needs and to determine the most suitable way to implement the appropriate coastal protection solutions.

Key Message 4

Human Health

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

Extreme heat causes both direct and indirect impacts on human health and acts as a threat multiplier to the medically vulnerable. The increase in extreme heat due to climate change will exacerbate the medical issues associated with heat illness. More detail can be found in Chapter 14: Human Health. Notably, heat stress is strongly correlated with complications of lung disease, such as asthma and emphysema, as well as dehydration and injurious electrolyte abnormalities. It is estimated that each increase of approximately 1.8°F (1°C) in summer temperature increases the death rate for elders with chronic conditions by 2.8% to 4.0%.¹⁴⁰ During heat waves, concrete, blacktop, and the low ventilation capacity of urban “canyons” created by tall buildings can add 7°–12°F to the urban heat load.¹⁴¹ The heat wave of 2011 exemplifies the human health and healthcare system impacts of extreme heat in the Southern Great Plains. The average temperature in Texas from June to August that year was 86.7°F (30.4°C), which broke all previous single-month records and was 5.2°F (2.9°C) higher than the long-term climatological average.¹¹ Studies demonstrated a 3.6% increase in emergency room visits and a 0.6% increase in deaths, with the largest effect on the elderly.^{142,143} Within the Southern Great Plains, changes in extreme temperatures are projected to result in an additional 1,300 deaths per year under a higher scenario (RCP8.5) by the end of the century. Under a lower scenario (RCP4.5), more than half of these additional deaths could be avoided. Annual losses associated with extreme temperature-related mortality are estimated at \$19 billion (2015 dollars) under RCP8.5 in 2090 and \$9.4 billion (2015 dollars) under RCP4.5¹⁴⁴ (see the Scenario Products section of App. 3 for more on RCPs).

Rising temperatures and precipitation alter the habitats of vectors (mosquitoes, ticks, rodents, and fleas) that transmit a variety of human diseases. In the Southern Great Plains, hantavirus,¹⁴⁵ Rocky Mountain spotted fever,¹⁴⁶

leptospirosis,¹⁴⁷ and West Nile virus¹⁴⁸ are all currently endemic and could be impacted by climate change.^{149,150} A warmer world will create newly hospitable habitats for tropical and subtropical insect vectors and the diseases they carry. Historically disease-free areas have been protected from becoming hazardous by cold environmental temperatures. That is, with extreme low temperatures of winter, insect (in particular, mosquito) populations are decimated. However, as the global average temperature increases, mosquitoes will thrive longer and reproduce more successfully at higher latitudes and altitudes. Tropical diseases, such as dengue virus,¹⁵¹ chikungunya virus, and Zika virus are transmitted by *Aedes* mosquitoes, which are currently expanding their geographic range in the southern United States.¹⁴⁹ In southern Texas, sporadic, locally acquired outbreaks of dengue have been reported.¹⁵² In 2005, there were 59 cases of dengue virus in southern Texas that met criteria for dengue hemorrhagic fever,¹⁵³ indicating that inhabitants were exposed to multiple variations of the virus, a condition necessary for the development of severe manifestations of dengue. In 2014, locally transmitted cases of chikungunya began to be reported in Texas.¹⁵⁴ Zika virus has also recently appeared in the region. In 2016, the Centers for Disease Control and Prevention (CDC) issued a travel warning for Cameron County, Texas, after the first case of local, person-to-person transmission of Zika was reported.¹⁵⁵ The ecology of vector-borne diseases is complex, and the future risk for proliferation and expansion of the ranges of these diseases is possible under future climate scenarios.^{156,157} Along the southern Gulf Coast, stronger hurricanes will increase the likelihood of favorable ecologic niches for emerging infectious diseases that infect humans and animals.¹⁵⁸

As water evaporates during periods of drought, the remaining water can have higher

concentrations of chemicals and solid particles, lower dissolved oxygen levels, and a higher density of germs that cause infectious diseases.¹²⁸ Drought conditions reduce the number of sources and overall quantity of water available to both human and animal users. Because these users are sharing a reduced supply, germ transmission and outbreaks of infectious disease become more likely. Waterborne diseases that have been linked to drought include amoebiasis, hepatitis A, salmonellosis, schistosomiasis, shigellosis, typhoid and paratyphoid fevers, infection with *E. coli*, cholera, and leptospirosis.^{159,160,161,162} Skin infections, such as scabies and impetigo, and eye infections, including conjunctivitis, are also correlated with drought due to a lack of water available for personal hygiene.¹⁶³

Droughts, floods, and higher temperatures will change the balance of ecosystems, allowing invasive species such as animal pests, plant weeds, and algae blooms to proliferate and harm existing agriculture.¹⁶⁴ Such conditions favor fungal species that can overwhelm crops and contaminate animal feedstocks. Additionally, increases in CO₂ are changing the nutritional composition of food crops.¹⁶⁵ Elevated CO₂ levels have been shown to reduce the protein composition of grains, tubers, rice, wheat, and barley.¹⁶⁶ Micronutrient contents are also affected by rising CO₂ levels, with atmospheric CO₂ concentrations of 550 parts per million being associated with reductions in zinc, iron, phosphorus, potassium, calcium, sulfur, magnesium, copper, and manganese across a wide range of crops.¹⁶⁷ Additionally, extreme temperatures and aridity pose health risks to outdoor agricultural workers.¹⁶⁸ Under a higher scenario (RCP8.5), the impact of temperature extremes at a national level are projected to result in the loss of two billion labor hours, equating to an estimated \$160 billion (in 2015 dollars) in lost wages by the end of the century. The Southern Great Plains region

is projected to experience higher-than-average impacts, with some communities projected to lose more than 6% in annual labor hours by the end of the century.¹⁴⁴

State-level climate adaptation programs¹⁶⁹ have been developed throughout the Nation. For health, these include vulnerability and adaptation assessments, comprehensive response plans,^{170,171} climate-proofing healthcare infrastructure, and implementing integrated surveillance of climate-sensitive infectious diseases. These efforts are outlined in more detail in Chapter 14: Human Health. Incorporating short-term to seasonal forecasts into public health activities can also provide assistance under a warming climate.¹⁷² Although there is momentum to adopt adaptation strategies in the wake of Hurricane Harvey,¹⁷³ and adaptation strategies on a general scale (such as for drought) are in progress,¹⁷⁴ large-scale adaptation efforts in the region are lacking¹⁷⁵ and regional planners can learn from activities ongoing outside the region (Ch. 14: Human Health).

Key Message 5

Indigenous Peoples

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

Box 23.2: The Sun Dance Ceremony

Cheyenne tribal Chief Gordon Yellowman noted that excessive heat, invasive species, and drought threatened the Cheyenne Sun Dance ceremony. He related how natural materials are traditionally gathered for the ceremony by young men, called runners. Most significantly, willow branches for shade arbors were increasingly hard to find given the prolonged drought experienced in western Oklahoma. In areas where natural materials were gathered for the ceremony, invasive poison ivy was now present, with the vines choking out willow saplings and taking over. Many of the young men were poisoned to such an extent that they had to seek medical attention beyond traditional medicines in order to participate in the most important ceremony for the Cheyenne. In addition, an increase in the occurrences of heat illness at these ceremonies is preventing some tribal members from participating in or completing the ceremony.



Figure 23.10: Chief Gordon Yellowman is shown here representing the Cheyenne Tribe at a traditional speaking engagement. Photo courtesy of Gordon L. Yellowman, Sr.

The 45 federally recognized tribes (48 if state-recognized tribal nations are included) located in the Southern Great Plains show considerable economic, social, cultural, and linguistic/language diversity.^{176,177,178} The 4 tribes of Kansas (59,130 people), 39 tribes of Oklahoma (482,760 people), including 1 state-recognized tribe, and 5 tribes of Texas (6,210 people), including 2 state-recognized tribes, experience the same climate change impacts as the rest of the Nation.¹⁴ However, these sovereign nations within the United States are faced with infrastructure (social and physical), economic, political, and cultural challenges, as well as unique opportunities, in their response to climate change impacts (Ch. 15: Tribes).

Climate Change Threats to Tribal Cultural Traditions and Community Resilience

No climate change impacts are as significant to the tribes and Indigenous peoples of the Southern Great Plains as those that threaten the ability to procure food, water, shelter, and preserve ancient cultural activities.^{179,180,181} Given the ancient symbiotic relationship between environment and culture that shapes tribal identities and life-way practices, climate-induced changes to the seasons, landscapes, and ecosystems pose an existential

threat to tribal cultural traditions and community resilience.^{182,183,184} For example, climate change, including the impacts of excessive heat, drought, and the disappearance of native species, is already disrupting ceremonial cycles in Oklahoma.¹⁸⁵ However, many climate change adaptation initiatives and strategies are being developed by tribes throughout the United States. Specific examples in the Southern Great Plains can be found in Figure 15.1 in Chapter 15: Tribes.

Physical and Organizational Infrastructure

The region's tribes and Indigenous peoples vary greatly in size, from small nations with fewer than 1,000 enrolled members to larger nations with over 50,000 enrolled members; the largest of the tribes is the Cherokee Nation with more than 317,000 enrolled members.¹⁸⁶ The smaller nations, given their population size and respective size of government, often struggle to exercise their sovereignty to respond to climate change due to a lack of organizational and physical infrastructure.^{187,188} The social organizational infrastructure needed to adapt to climate change impacts like extreme weather events, rising temperatures, shifting seasons, invasive species, air and water quality issues, and a host of health impacts

is often lacking or underdeveloped in small tribal nations. Consequently, the smaller tribes depend largely on the services, grant programs, and technology transfer capabilities of the Bureau of Indian Affairs and other Federal Government departments, agencies, and bureaus to assist in their climate adaptation efforts. There are exceptions—larger and wealthier tribal nations, such as the Chickasaw Nation, Citizen Band Potawatomi, and Muscogee (Creek) Nation, can develop and shape, to a much larger extent, their own climate adaptation strategies.¹⁶⁹

Lack of physical infrastructure, tied directly to limited economic resources and power, poses a substantial obstacle to climate change adaptation for the tribes of the region. While cities and other governmental jurisdictions make plans to build resilient physical infrastructure by using bonds, public-private partnerships, and taxes and tax instruments, only a handful of tribal nations have the ability to use these tools for climate adaptation. Most tribes and Indigenous peoples remain dependent on underfunded federal programs and grants for building and construction activities to improve the resilience of their infrastructure in the face of climate change threats. Many larger and wealthier tribes have modeled construction and design of homes and large commercial building best practices on “green” or resilient net-zero carbon footprint designs. Increasing activity in community gardens, food recovery, recycling, water conservation, land-use planning, and investment in climate-resilient community design all signal opportunities for tribal nations to leapfrog significant obstacles other city, county, and state governments face when dealing with the costs of existing physical infrastructure that often make climate change adaptation difficult and incremental.

Acknowledgments

Technical Contributor

Katharine Hayhoe
Texas Tech University

USGCRP Coordinators

Susan Aragon-Long
Senior Scientist

Christopher W. Avery

Senior Manager

Opening Image Credit

Whooping cranes: Jon Noll/U.S. Department of Agriculture.

Traceable Accounts

Process Description

The initial Southern Great Plains author team was selected such that expertise from each of the states' officially recognized climate offices in the region (Kansas, Oklahoma, and Texas) were included. The offices of the state climatologist in Kansas, Oklahoma, and Texas are each members of the American Association of State Climatologists, which is the recognized professional scientific organization for climate expertise at the state level.

One representative from each of several regional hubs of national and regional climate expertise was included on the author team. These regional hubs include the U.S. Department of Agriculture's Southern Plains Climate Hub (El Reno, Oklahoma), the U.S. Department of the Interior's South Central Climate Adaptation Science Center (Norman, Oklahoma), and the National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments Southern Climate Impacts Planning Program (Norman, Oklahoma).

After assessing the areas of expertise of the six authors selected from the state and regional centers, a gap analysis was conducted to prioritize areas of expertise that were missing. Due to the importance of the sovereign tribal nations to the Southern Great Plains, an accomplished scholar with expertise in Indigenous knowledge on the environment and climate change was selected from the premier tribal university in the United States, Haskell Indian Nations University in Lawrence, Kansas. An individual from the Environmental Science Institute at the University of Texas at Austin was selected to bring expertise on the complex intersection of coupled atmosphere–land–ocean systems, climate, and humans (population and urbanization). Expertise in the electric utility industry was gained through the Oklahoma Association of Electric Cooperatives by an individual with a long history of working with rural and urban populations and with researchers and forecasters in weather and climate.

The author group decided to allow Southern Great Plains stakeholders to drive additional priorities. On March 2, 2017, the Fourth National Climate Assessment (NCA4) Southern Great Plains chapter team held a Regional Engagement Workshop at the National Weather Center in Norman, Oklahoma, with a satellite location in Austin, Texas, that allowed a number of stakeholders to participate virtually. The objective of the workshop was to gather input from a diverse array of stakeholders throughout the Southern Great Plains to help inform the writing and development of the report and to raise awareness of the process and timeline for NCA4. Stakeholders from meteorology, climatology, tribes, agriculture, electric utilities, water resources, Bureau of Land Management, ecosystems, landscape cooperatives, and transportation from Kansas, Oklahoma, and Texas were represented. The productive dialog at this workshop identified important gaps in environmental economics, ecosystems, and health. Scientists working at the cutting edge of research in these three areas were selected: an ecosystems expert from the Texas Parks and Wildlife Department, an environmental economist from the department of Geography and Environmental Sustainability at the University of Oklahoma, and health experts from the University of Colorado School of Medicine and the Aspen Global Change Institute.

This diverse collection of medical doctors, academics, researchers, scientists, and practitioners from both federal and state agencies gives the Southern Great Plains chapter a wealth of expertise across the many ways in which climate change will affect people in the region.

Key Message 1

Food, Energy, and Water Resources

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

Description of evidence base

The connection between food, water, and energy also creates great challenges in the management and distribution of resources. People need food, energy, and water, yet all sectors pull from each other and allocation is a challenge. There are many studies focused on the competitive nature revolving around these resources and the demand by people.^{41,59,60,61,62,63,64,65} The management and application of these issues are social in context and require significant communication and collaboration to resolve. As demands for these resources become more acute, development of collaborative processes to ensure integrated use and allocation may be required.

Major uncertainties

Research into the intersection of food, energy, and water is in its early stages and historically tends to examine only one or two components.^{59,60,61,62,63,64,65} It is clear that tradeoffs and cascading complexities exist between sectors, and changes in one sector are likely to propagate through the entire system. There are significant gaps in the scientific understanding regarding the role that climate change will play as a disruptive force and a threat to food, energy, and water security.^{60,63,66,67,68} It is likely, and with significant certainty, that the competition for and use of the resources by people will continue; however, the likelihood of developing a means to manage this situation is challenging. The added complexities of people and cultures, a rapidly growing population (see next section), and the diminishing availability of resources (water especially) in this region will be an important future research topic.

Description of confidence and likelihood

The Southern Great Plains will continue to grow rapidly and with high probability of significant competition. Water is the major concern, and political inability to develop a system to allocate water in an equitable manner will continue to build this competitive and contentious issue among all users—energy, food, and water. Quality of life in the region will be compromised as population increases. At least 60% of the region's population is clustered around urban centers currently, but these population centers are experiencing growth that far exceeds that of rural communities. The remaining population is distributed across vast areas of rural land.^{14,30,31,32,33} Therefore, the migration of individuals from rural to urban locations, combined with climate change, redistributes

demand at the intersection of food consumption, energy production, and water resources. (*Likely, High confidence*)

A growing number of adaptation strategies, improved climate services, and early warning decision support systems will more effectively manage the complex regional, national, and transnational issues associated with food, energy, and water. Since a changing climate has significant negative impacts on agriculture in the United States and causes substantial economic costs,³⁸ the effects of drought and other occurrences of extreme weather outside the region will also affect the food–energy–water interconnections within the region. (*Likely, High confidence*)

Key Message 2

Infrastructure

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

Description of evidence base

The existing infrastructure and projected models for growth are well established and documented. Demographic and population projections are available from state demographers and are typically included in Long-Term Transportation Plans available from state departments of transportation. Additionally, the present-day infrastructure challenges have been examined in depth by the American Society for Civil Engineers (ASCE), which publishes an Infrastructure Report Card for the Nation and for each state (www.infrastructurereportcard.org).¹⁸⁹ For the Southern Great Plains states, one of the pressing concerns is meeting the funding challenges necessary to maintain critical infrastructure, as well as anticipating future revenue streams, which themselves depend on population and its distribution, and state and federal funding. The ASCE, as well as all state transportation plans in the Southern Great Plains, does not consider future climate projections, and the information contained generally does not explicitly mention climate-related stressors. However, the impacts of climate change have become an issue of concern for agencies such as the Department of Transportation (DOT) and Federal Highways Administration (FHWA), which have in recent years funded projects evaluating the potential impacts of climate change on infrastructure and transportation and possible adaptation strategies. Since 2010, the FHWA has sponsored a series of pilot studies in resilience for municipalities and states across the Nation.¹⁹⁰ Two of these studies took place in Texas, in Dallas and Tarrant Counties and in the City of Austin. These reports provide some of the most comprehensive examples of integrating climate data into assessments of infrastructure vulnerability in the region to date. The potential impacts of temperature and precipitation extremes on transportation and infrastructure were based in part on known vulnerabilities as shown by these aforementioned reports and the larger repository of information and resources supplied by the FHWA.

Estimates of relative sea level rise (SLR) in Texas in the historical period are available from NCA4 Volume I: *Climate Science Special Report*,²⁴ Runkle et al. (2017),²⁵ Sweet et al. (2017).¹⁹¹ Relative SLR along the Texas coastline is some of the highest in the Nation; coupled with its population and critical energy infrastructure, this region has some noteworthy vulnerabilities to SLR. Projections of SLR remain uncertain and depend to some extent on whether the current rates of relative SLR are maintained, in addition to the magnitude and rate of greenhouse gas emissions. Sweet et al. (2017)¹⁹¹ probabilistically evaluate a number of SLR scenarios, typically noting that the Texas coast SLR is higher than the global mean. The values mentioned in the main text are global mean values obtained from USGCRP (2017)²⁴ and from the range quoted by Runkle et al. (2017).²⁵

Major uncertainties

In the Southern Great Plains there remains uncertainty over the direction of change of average precipitation, although models generally project increases in very heavy precipitation.¹ The expectation of an increase in the frequency of events such as the 100-year storm is uncertain due to the spread of model projections of extreme precipitation and the need to use additional statistical modeling in order to obtain the return period estimates.

There are limited studies that attempt to directly link weather and climate extremes and their impacts to infrastructure. While it is appreciated that infrastructure exposed to adverse conditions will lead to deterioration, studies on specific cause-effect chain of events in these cases are limited (e.g., Winguth et al. 2015¹⁹²). The results are more evident in the case of catastrophic failures associated with floods, for example, but even in those cases, antecedent conditions related to the age, condition, and/or construction quality of infrastructure will affect its resilience (Ch. 12: Transportation).

Description of confidence and likelihood

There is *very high confidence* that extreme heat will increase in frequency and intensity. There is *medium confidence* in an increased frequency of flooding and *high confidence* in the increased frequency of drought. There is *high confidence* of sea level rise of at least 4 feet by 2100 along the Texas coastline if greenhouse gas emissions are not reduced. On the implications for infrastructure, there is *high confidence* that weather-related damage will increase due to inland weather-related hazards. Along the coastline, there is *very high confidence* that infrastructure will be impacted by sea level rise and storm surge.

Key Message 3

Ecosystems and Ecosystem Services

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

Description of evidence base

This Key Message was developed through technical discussions developed within science teams and collaborators of the Gulf Coast and Great Plains Landscape Conservation Cooperatives. Species' response to climate change is complex and variable;¹¹⁹ this complexity necessitates a multifaceted review of the projected impacts of climate change. In addition, ecosystem services also require assessment, given the impact of climate change on their ability to deliver materials and processes that benefit people.¹²³

The following relevant areas of evidence regarding climate change impacts on ecosystems in the Southern Great Plains were therefore considered: species, aquatic ecosystems, coastal bays and estuaries, and risk management. It is unclear how climate change will affect species directly, but the effects of increased aridity will likely have negative impacts (e.g., NFWPCAP 2012¹²³). Species migration (e.g., Schmandt 2011¹²⁶) and mortality (e.g., Moore et al 2016¹²⁷) will increase in response to climate change. Climate change impacts to aquatic ecosystems include higher water temperatures in lakes, wetlands, rivers, and estuaries, while impacts to reservoirs include fluctuating lake levels, loss of habitat, loss of recreational access, increase in harmful algal blooms, and disconnectedness from upstream and downstream riverine habitat.¹²⁹ Sea level rise will impact coastal bays and estuaries via more frequent and longer-lasting flooding of marshes,^{126,132} while higher tides and storm surges cause inundation of freshwater areas and beach erosion, leading to a potential decrease or loss of barrier islands and coastal habitats, including nesting habitats and submerged habitats such as seagrass beds affected by changes in water quality and changing water depths.¹³³ Other ecosystem-centered impacts include surface and groundwater depletion (e.g., Perkin et al. 2017¹³⁴) and changes in migratory species pathways.¹³⁵

Major uncertainties

Ecosystems and the species that exist in these ecosystems have experienced a rapid decline in many “common species” as well as certain rare species.^{123,137,138} Increases in many nonnative species have led to both concern and opportunity. Continued habitat and population shifts and the impact of interactions between people, other resources, and available habitat stressors are vague. Indirect impacts to livestock and agricultural systems are also unknown. The likelihood of animal and plant diseases and parasites impacting commercial production and the interaction with wild species is anticipated but uncertain.

Description of confidence and likelihood

There is *high confidence* that rising temperatures and increases in flooding, runoff events, and aridity will *likely* lead to changes in the aquatic and terrestrial habitats supporting many regional species. Flooding has changed the complexity of many riparian habitats. Increases already seen in extreme drought occurrence have caused downturns in the fish- and wildlife-related industries, with losses in traditional fish (crab and oysters) and wildlife species (waterfowl) important for both recreational and commercial purposes.

In contrast, habitat created by invasive species due to climate change has improved populations of other species including fungi. The expanded stress due to a rapidly growing population in this region increases the likelihood (*high confidence*) of negative natural resource and ecosystems outcomes in the future.

Key Message 4

Human Health

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

Description of evidence base

This Key Message was developed in close coordination with the Human Health (Ch. 14) author team and incorporated applicable inputs from the U.S. Climate and Health Assessment.¹⁶⁸ Multiple lines of evidence demonstrate statistically significant associations between temperature, precipitation, and other climatologic variables with adverse health outcomes, including heat-related illness, respiratory disease, malnutrition, and vector-borne disease.¹⁶⁸ Regionally specific examples of these well-documented impacts were identified through literature reviews conducted to identify regionally specific studies of these impacts.

There is strong evidence that increasing average temperatures as well as increasing frequency, duration, and intensity of extreme heat events will occur in the Southern Great Plains by the middle and end of this century, with higher CO₂ emissions leading to greater and faster temperature increases.⁸⁰ Extreme temperatures are shown with *high confidence* to have substantial effects on morbidity and mortality^{142,143,168} by causing heat-related illness and by increasing the risk of cardiovascular events, cerebrovascular events, respiratory disease, renal failure, and metabolic derangements.^{193,194} In addition to impacting health and well-being, extreme heat is likely to lead to a significant economic impact through an increase in healthcare costs, premature mortality, and lost labor.¹⁹⁵ Within the Southern Great Plains, climate change is likely to exacerbate aridity due to drying of soils and increased evapotranspiration caused by higher temperatures.⁸⁰ Such aridity is likely to negatively impact the agricultural sector, contributing to food insecurity and increased pesticide use.¹⁶⁵ Extreme temperatures are projected to further impair food production in the region by significantly impacting the health and work capacity of outdoor workers.¹⁴⁴ Additionally, shifting temperature and precipitation patterns are making habitats more suitable for disease-carrying vectors to move northward towards the Southern Great Plains region.^{149,150} In southern Texas, sporadic, locally acquired outbreaks of dengue, chikungunya, and Zika have been reported.^{152,154,155} These diseases are transmitted by the *Aedes aegypti* mosquitoes, which are currently expanding their geographic range into the Southern Great Plains region.^{149,196}

Climate change is expected (with *medium to high confidence*) to increase the frequency of extreme rainfall and hurricanes, although impacts in the Southern Great Plains remain difficult to quantify.² The Gulf Coast of Texas in particular has experienced several record-breaking floods and tropical

cyclones in recent years, including Hurricane Harvey. Hurricanes and resultant flooding result in significant health impacts, including deaths from drowning and trauma, critical shortages of essential medications, critical healthcare system power shortages, and forced patient evacuations.⁹ Such events strain healthcare resources not only within regions of direct hurricane impact but also within the entire region due to displacement of patient populations.⁸

Major uncertainties

The ability to quantitatively predict specific health outcomes associated with projected changes in climate is limited by long-term public health data as well as meteorological data. While assessments consistently indicate that climate change will have direct and indirect impacts on human health (*high confidence*), quantifying specific health metrics, such as incidence and community level prevalence, remains difficult. The uncertainty develops when there are many connected actions that influence health outcomes. For example, the future impact of climate change on human health is likely to be reduced by adaptation measures that take place on local and national scales. Additionally, the role of non-climate factors, including land use, socioeconomic, and population characteristics (such as immigration), as well as health sector policies and practices, will affect local and regional health impacts. The magnitude of impact of these variables on health at local and regional scales is difficult to predict. The estimation of future economic impacts is limited by difficulties in estimating the true cost of healthcare delivery and additionally only partially captures the actual impacts on health and livelihood of individuals and communities. Thus, existing projections likely underestimate the entirety of the economic impact.

Description of confidence and likelihood

There is *very high confidence* that rising temperatures and changes in precipitation leading to flooding, runoff events, and aridity will *likely* lead to negative impacts on human health in the Southern Great Plains. There is *high confidence* that certain populations, such as very young and old and socioeconomically disadvantaged individuals, will *likely* be disproportionately affected.

Key Message 5

Indigenous Peoples

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

Description of evidence base

This Key Message was developed through dialog and discussions among Indigenous communities and within the social sciences discipline. While Indigenous communities vary in size from smaller nations to large well-formed governments, all are in need of communication about the realities of climate change.¹⁴ Climate change threatens the ability of tribes and Indigenous peoples to procure food, water, and shelter and to preserve ancient cultural activities.^{179,180,181} The impacts of excessive

heat, drought, and the disappearance of native species are already disrupting ceremonial cycles in Oklahoma.¹⁸⁵ There is strong evidence that because of the unique nature of the Indigenous communities, including previous and ongoing experiences of the communities, the collective economic and political power for enacting efficient and effective climate adaptation responses could be limited at best.^{182,183,184} There is a consensus among the nations that impacts of climate change will be a direct threat to the symbiotic connection between environment and the tribal traditions connecting the people with the land.

Major uncertainties

There is a great deal of uncertainty regarding how tribal communities will integrate climate change into their cultures, given the variable size of these communities and the challenges of connecting and communicating with clarity among them. It is likely that adaptation strategies will vary greatly as knowledge and communication might not be widely supported within all nations.^{169,187,188} Due to disproportionate rates of poverty and access to information and collaborative support, some communities could suffer more than others; however, the degree and the impacts of such are unclear.

Description of confidence and likelihood

There is *high confidence* that extreme events and long-term climate shifts will lead to changes in tribal and Indigenous communities in the Southern Great Plains. Environmental connections will be direct, but the degree of those connections is uncertain and shifts in climate system will impact each nation differently. How changes will be perceived and managed and what steps are taken to adapt are uncertain; thus, there is *low confidence* that adaptation will be a successful mechanism among all tribal and Indigenous peoples.

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Northwest

Federal Coordinating Lead Author

Charles Luce

USDA Forest Service

Chapter Lead

Christine May

Silvestrum Climate Associates

Chapter Authors

Joe Casola

Climate Impacts Group, University of Washington

Michael Chang

Makah Tribe

Jennifer Cuhaciyen

Bureau of Reclamation

Meghan Dalton

Oregon State University

Scott Lowe

Boise State University

Gary Morishima

Quinault Indian Nation

Philip Mote

Oregon State University

Alexander (Sascha) Petersen

Adaptation International

Gabrielle Roesch-McNally

USDA Forest Service

Emily York

Oregon Health Authority

Review Editor

Beatrice Van Horne

USDA Forest Service, Northwest Climate Hub

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Key Message 1

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

Natural Resource Economy

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

Key Message 2

Natural World and Cultural Heritage

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

Key Message 3

Infrastructure

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

Key Message 4

Health

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

Key Message 5

Frontline Communities

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

Executive Summary



Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The region is known for clean air,

abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Climate change, including gradual changes to the climate and in extreme climatic events, is already affecting these valued aspects of the region, including the natural resource sector, cultural identity and quality of life, built infrastructure systems, and the health of Northwest residents. The

communities on the front lines of climate change—tribes and Indigenous peoples, those most dependent on natural resources for their livelihoods, and the economically disadvantaged—are experiencing the first, and often the worst, effects.

In the Third National Climate Assessment, the Key Messages for the Northwest focused on projected climate impacts to the region.¹ These impacts, many of which are now better understood in the scientific literature, remain the primary climate concerns over the coming decades. In this updated assessment, the Key Messages explore how climate change could affect the interrelationships between the environment and the people of the Northwest. The extreme weather events of 2015 provide

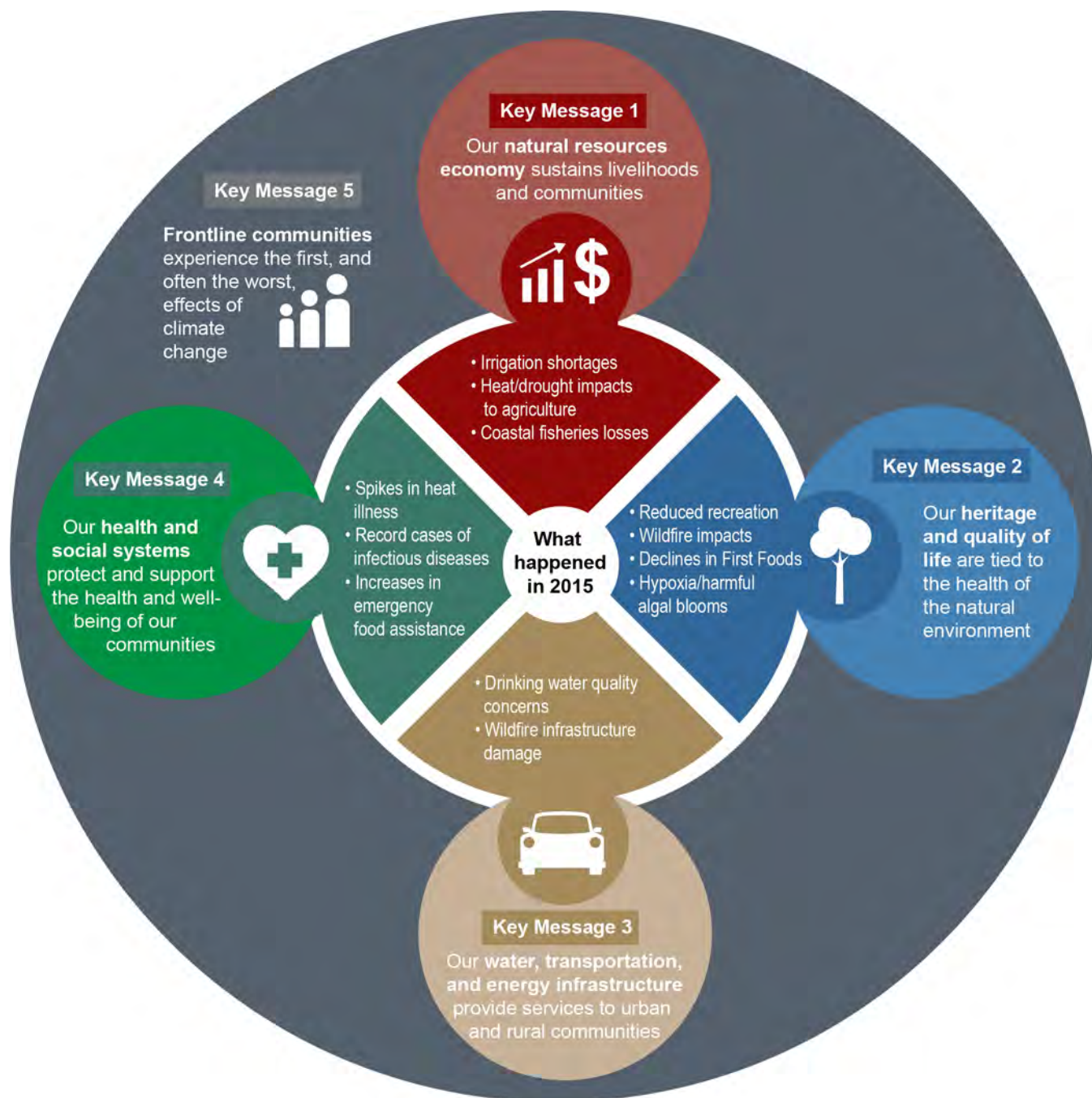
an excellent opportunity to explore projected changes in baseline climate conditions for the Northwest. The vast array of climate impacts that occurred over this record-breaking warm and dry year, coupled with the impacts of a multiyear drought, provide an enlightening glimpse into what may be more commonplace under a warmer future climate. Record-low snowpack led to water scarcity and large wildfires that negatively affected farmers, hydropower, drinking water, air quality, salmon, and recreation. Warmer than normal ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom that adversely affected the region's fisheries and shellfish harvests.

Strong climate variability is likely to persist for the Northwest, owing in part to the year-to-year and decade-to-decade climate variability associated with the Pacific Ocean. Periods of prolonged drought are projected to be interspersed with years featuring heavy rainfall driven by powerful atmospheric rivers and strong El Niño winters associated with storm surge, large waves, and coastal erosion. Continued changes in the ocean environment, such as warmer waters, altered chemistry, sea

level rise, and shifts in the marine ecosystems are also expected. These changes would affect the Northwest's natural resource economy, cultural heritage, built infrastructure, and recreation as well as the health and welfare of Northwest residents.

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

Climate Change Will Impact Key Aspects of Life in the Northwest



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

Background

Residents of the Northwest list the inherent qualities of the natural environment among the top reasons to live in the region. The Northwest is known for clean air, abundant water, low-cost hydroelectric power, vast forests, extensive farmlands, and an array of outdoor recreation that includes hiking, boating, fishing, hunting, and skiing. Warming and related changes in climate are already affecting aspects of the Northwest's identity such as its natural resource economy and its cultural heritage that is deeply embedded within the natural environment. The built systems that support Northwest residents and the health of residents themselves are also already experiencing the effects of climate change. The communities on the front lines of climate change experience the first, and often the worst, effects. Frontline communities in the Northwest include tribes and Indigenous peoples, the economically disadvantaged, and those most dependent on natural resources for their livelihoods.

The region has warmed substantially—nearly 2°F since 1900—and this warming is partially attributable to human-caused emissions of greenhouse gases.^{2,3,4} Warmer winters have led to reductions in the mountain snowpack^{5,6} that historically blanketed the region's mountains, increasing wildfire risk (Ch. 6: Forests, KM 1)^{7,8} and speeding the usually slow release of water for communities, agriculture, rivers, and soils. In 2015, record winter warmth led to record-low snowpack in much of the Northwest's mountains as winter precipitation fell as rain instead of snow,⁹ resulting in drought, water scarcity, and large wildfires that negatively affected farmers, hydropower, drinking water, salmon, and recreation. In addition, warmer ocean temperatures led to shifts in the marine ecosystem, challenges for salmon, and a large harmful algal bloom.¹⁰ The extreme



Detroit Lake Reservoir During Multiyear Drought

Figure 24.1: Detroit Lake Reservoir in Oregon at record-low levels in 2015. Photo credit: Dave Reinert, Oregon State University.

climate-related events of 2015 have prompted Northwest states, cities, tribes, and others to increase and prioritize climate preparedness efforts, as evidenced by the presentations at the 6th and 7th annual Northwest Climate Conference (<http://pnwclimateconference.org/CdA2015/> and <http://pnwclimateconference.org/Stevenson2016/>).

Climate change affects the interrelationships between the environment and the people of the Northwest, and extreme climate events, such as those that occurred during 2015, provide a preview of what may be more commonplace under a warmer future climate (Figure 24.2). The Northwest is projected to continue to warm during all seasons under all future scenarios, although the rate of warming depends on current and future emissions.¹¹ The warming trend is projected to be accentuated in certain mountain areas in late winter and spring,⁹ further exacerbating snowpack loss and increasing the risk for insect infestations and wildfires.¹² In central Idaho and eastern Oregon and Washington, vast mountain areas have already been transformed by mountain pine beetle infestations, wildfires, or both, but the western Cascades and coastal mountain ranges have less experience with these growing threats.¹³

Climate Change Will Impact Key Aspects of Life in the Northwest

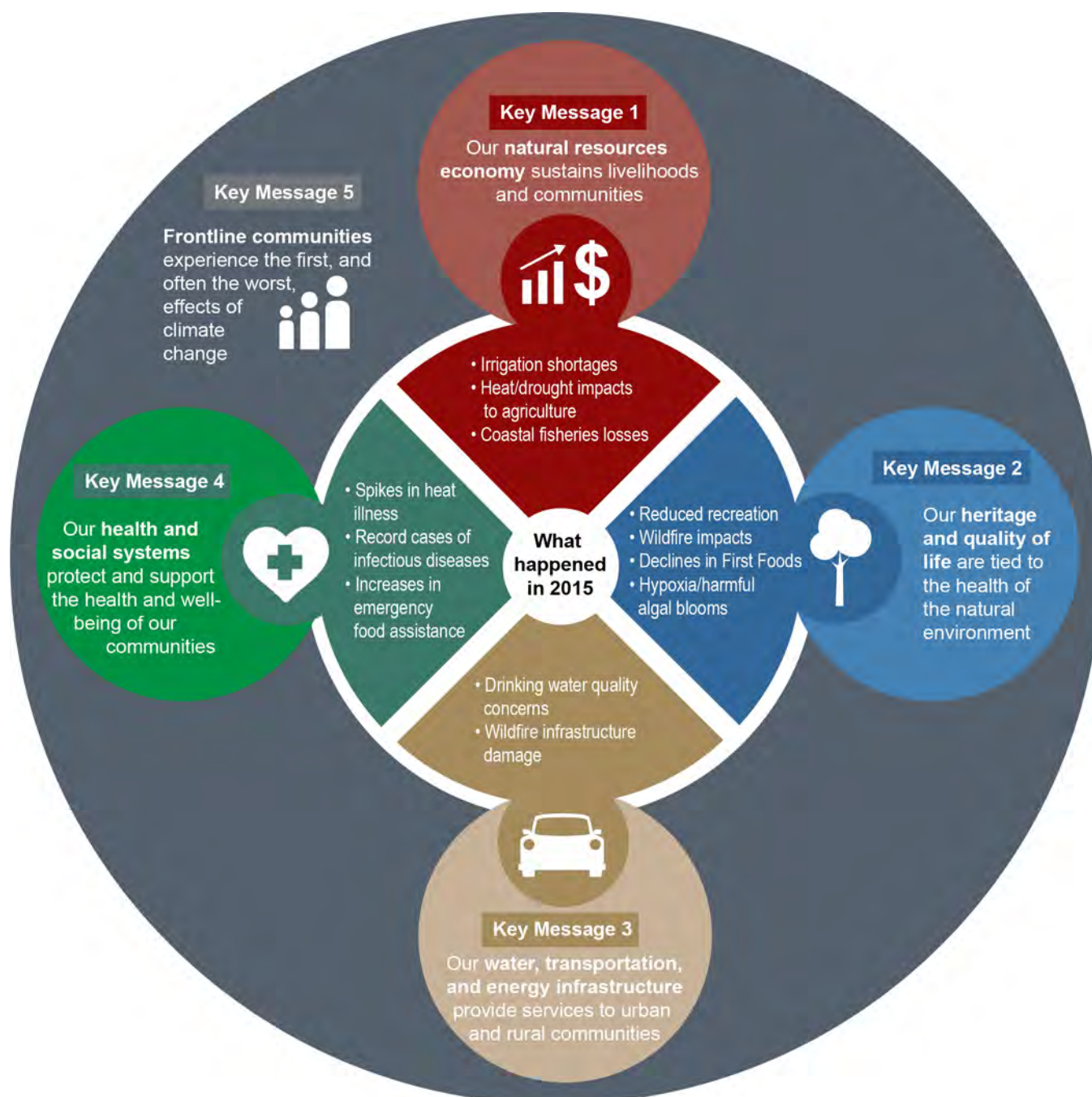


Figure 24.2: The climate-related events of 2015 provide a glimpse into the Northwest's future, because the kinds of extreme events that affected the Northwest in 2015 are projected to become more common. The climate impacts that occurred during this record-breaking warm and dry year highlight the close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

Average winter precipitation is expected to increase over the long term, but year-to-year variability in precipitation is also projected to increase.¹¹ Years of abnormally low precipitation and extended drought conditions are expected to occur throughout the century,¹¹

and extreme events, like heavy rainfall associated with atmospheric rivers, are also anticipated to occur more often.¹⁴ Along the coast, severe winter storms are also projected to occur more often, such as occurred in 2015 during one of the strongest El Niño events on

record.¹⁵ El Niño winter storms contributed to storm surge, large waves, coastal erosion, and flooding in low-lying coastal areas (Ch. 8: Coastal, KM 1).¹⁶ Changes in the ocean environment, such as warmer waters, altered chemistry, sea level rise, and shifts in the marine ecosystems are also expected (Ch. 9: Oceans). These projected changes affect the Northwest's natural resource economy, cultural heritage, built infrastructure, recreation, and the health and welfare of Northwest residents.

Key Message 1

Natural Resource Economy

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

Linkage Between Observed Climate and Regional Risks

The Northwest provides for a diverse natural resource economy, from coastal fisheries, to Douglas fir plantations, to vineyards, to semiarid rangelands, to dryland and irrigated farms. The region is the Nation's top producer of 28 agricultural products, one of the leading national producers of timber products, and is widely recognized for salmon and shellfish fisheries. The agriculture, forestry, and fisheries sectors accounted for over 700,000 jobs and more than \$139 billion in sales in 2015 (in 2015 dollars; Figure 24.3).¹⁷

Natural Resource Industry Jobs and Sales Revenues



Figure 24.3: Natural resources are a key part of the Northwest economy. Climate change is putting natural resource sector jobs and sales revenues at risk. Jobs and sales figures include the agriculture, forestry, and fisheries sectors only, and are presented based on 2015 data for Idaho, Oregon, and Washington.¹⁷ Source: U.S. Forest Service and Boise State University.

The outdoor recreation sector is another important contributor to local economies in the Northwest. The Outdoor Industry Association (2017)¹⁸ estimates that the region's outdoor recreation economy generates \$51 billion (based on 2017 data, dollar year not reported) in consumer spending each year and provides around 451,000 jobs. These economic benefits are particularly important in rural and tribal communities whose income base is largely dependent on natural resource economies and supporting industries (Ch. 10: Ag & Rural, KM 4; Ch. 15: Tribes). Outdoor activities, including skiing, boating, rafting, hunting, fishing, hiking, and backpacking, are impacted by climate variability, whether through less summer water, warmer streams, less snowfall, or loss of forests. Comparing high-snowfall to low-snowfall years in the Northwest between 1999 and 2009, each low-snowfall year resulted in more than 2,100 fewer employees and a \$173 million reduction in ski resort revenues (\$189 million in 2015 dollars) compared to the high-snowfall years.¹⁹ Impacts on the skiing industry were especially prominent during

the warm 2015 winter, when snowpack was at record lows (see Box 24.7).

Both the natural resource commodity sector and the outdoor recreation industry are sensitive to short- and long-term climate variability. The record-setting 2015 drought and above-average temperatures were a challenge for agriculture. The reduced availability of water for irrigation coupled with heat stress impacted production and livestock health (see Box 24.7) (see also Ch. 10: Ag & Rural, KM 2 and 3; Ch. 3: Water, KM 3). In Northwest forests, tree mortality driven by wildfires, insects, and disease have been more prevalent over the last two decades due to drought conditions and increased temperatures (e.g., Hicke et al. 2013¹³), and timber managers are adjusting to increased risk of loss by shortening rotation rates, reducing investment in some areas, and changing planted species.^{20,21}

Commercial fisheries are also sensitive to climate variability. River temperatures increase during warm and dry years, resulting in fish kills of migrating and spawning salmon; these fish kills have consequences several years in the future.^{22,23,24} In 2015, July water temperatures in the lower Columbia River and its tributaries were higher than in any other year on record, leading to a high rate of mortality for endangered sockeye and threatened Chinook.^{25,26} The record temperatures in 2015 were part of a long-term trend of declining low flows²⁷ and warming streams.^{28,29} Increasing ocean temperatures and acidity also impact fish survival, species abundance, and predator-prey distribution and timing.³⁰ In 2015, the increased ocean temperatures were part of an ocean heat wave coined “the Blob,” which fueled a coast-wide harmful algal bloom that affected commercial, recreation, and tribal subsistence fisheries (see Box 24.7) (see also Ch. 9: Oceans).¹⁰

Future Climate Change Relevant to Regional Risks

Shifts in timing of water supply, such as earlier snowmelt and declining summer flows, can adversely impact irrigated crop productivity, particularly where access to reservoir water storage and/or groundwater is limited (Ch. 10 Ag & Rural, KM 2).³¹ Planning studies for Northwest reservoirs suggest a significant increased need for reservoir storage to meet future summer irrigation demands under climate change scenarios.^{32,33} Irrigation demands among farmers in the Columbia River Basin are projected to increase 5% in response to climate change by the 2030s; however, actual water demands will vary depending on adaptive management decisions and crop requirements.³⁴ For dryland wheat production, shifting planting dates and rising temperatures coupled with increased atmospheric carbon dioxide (CO₂) and associated increases in plant water use efficiency are projected to lead to improved wheat yields under both lower and higher scenarios (RCP4.5 and RCP8.5) through the end of the century.^{35,36}

Specialty crops, including apples and other tree fruits, are already experiencing changes. Higher spring temperatures have led to earlier flowering, which can lead to a mismatch with the availability of pollinators required for fruit setting (the process of flowers becoming fruit)³⁷ and can affect fruit quality as well as yield. Additionally, summer heat stress can lead to sunburn scald on apples and softer berry crops that can be damaged in transport and harvest,³⁷ which can decrease fruit quality and the farmers’ selling price. Heat stress can also decrease livestock health and increase parasite abundance.³⁸ Projected warmer and drier summer seasons will likely reduce forage quality and quantity,³⁹ with varied impacts across forage and rangeland types.⁴⁰ Impacts to the quality and quantity of forage will also likely impact farmers’ economic viability as they may need to buy additional feed or wait longer for their

livestock to put on weight, which affects the total price they receive per animal.

Forests in the interior Northwest are changing rapidly because of increasing wildfire⁸ and insect and disease damage,^{41,42} attributed largely to a changing climate (Ch. 5: Land Changes).⁴³ These changes are expected to increase as temperatures increase⁴⁴ and as summer droughts deepen.⁴⁵ For forests that grow in areas with snowpack, the declining snowpack is projected to worsen summer drought conditions, increasing vulnerability to drought caused by year-to-year precipitation variability.⁴⁶ Some forests in the region will increase in potential productivity (growth without consideration of increased disturbance) due to a combination of increased CO₂ and a longer growing season length, while others will decrease due to reduced availability of summer moisture (Ch. 6: Forests).⁴⁷ Timber supplies from the drier eastern Northwest forests are the most affected by climate-related disturbances,⁴⁸ resulting in intermittent and unpredictable timber supplies and depressed timber prices⁴⁹ in an already difficult global market. This could affect mill investments and the long-term viability of forestry as an economic activity, particularly in the more remote areas of the region where transportation costs to mills are high.

The negative impacts on Northwest fisheries associated with ocean warming, acidification, and harmful algal blooms are expected to increase (Ch. 9: Oceans).⁵⁰ This could lead to extensive fisheries closures across all of the region's coastal fisheries, with severe economic and cultural effects on commercial and subsistence shellfish industries. The warming ocean is projected to result in range shifts, with some Northwest species shifting as far north as the Bering Sea.⁵¹ However, these range shifts may also open up new fishing opportunities in the Northwest,^{51,52} depending on interstate

and international coordination between management agencies. As the marine ecosystems respond to climate change, there will likely be consequences to existing place-based fisheries resources, as well as potential benefits and new resources. How the shifting resources will be managed and how existing fishing rights and allocations will change over time is currently not known (Ch. 9: Oceans, KM 2).

Projections for increased stream temperature indicate a 22% reduction in salmon habitat in Washington by late century under a high emissions future (the A1F1 scenario).⁵³ This habitat loss corresponds to more than \$3 billion in economic losses due to reductions in salmon populations and decreases in cold-water angling opportunities (\$3.3 billion in 2015 dollars, discounting method not specified).⁵³ Freshwater trout are sensitive to habitat connectivity and wildfire, so land management practices will affect how trout respond to climate change.⁵⁴ Overall, commercial fishing performance and abundance are expected to decline as the climate changes.^{50,55,56,57}

Decreases in low- and mid-elevation snowpack and accompanying decreases in summer streamflow are projected to impact snow- and water-based recreation, such as downhill and cross-country skiing, snowmobiling, boating, rafting, and fishing. Climate change could decrease snow-based recreation revenue by more than 70% annually in the Northwest under a higher scenario (RCP8.5).⁵⁸ Impacts to snowpack and, consequently, winter recreation will likely occur later in the colder, higher-elevation mountains in southern Idaho.⁵⁹

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change will likely have both positive and negative effects on the natural resource sector; however, cost-effective adaptation approaches that build agro-ecosystem

resilience are likely needed to maintain agricultural livelihoods (see Box 24.1). A shift in plant hardiness zones, or the ability of a given plant to thrive in a specific location, is expected, changing the suitability of growing certain crops in specific locations;^{60,61} such shifts may change land uses entirely (Ch. 5: Land Changes, KM 2). For example, Northwest wine producers may see the potential for growing higher-quality and higher-value wine grape varieties,⁶² but changing hydrologic regimes are projected to limit available water supplies for irrigation, requiring water storage or alternative water sources to maintain productivity. Over the longer term, changes to average growing season temperatures and the number of severe hot days are projected to reduce premium wine grape production in the Northwest, potentially shifting prime growing areas further north.⁶³ To take advantage of shifting opportunities, farmers would need to consider costly changes and investments in new farming practices and territories in advance of projected climate change.^{37,64}

Livestock producers in the Northwest have an advantage over those in other U.S. regions where climate change impacts are likely to be more severe (Ch. 10: Ag & Rural, KM 3).⁶⁵ However, livestock production costs are still likely to increase in the Northwest due to supplemental feeding and watering requirements and the need for reducing livestock numbers in response to warmer and drier summers.⁴⁰

The prevalence of wildfires, insect infestations, disease epidemics, and drought-induced dieback of Northwest forests have heightened forestry managers' awareness of potential climate change impacts. Over the long term, these sustained impacts are projected to fundamentally alter forest composition and land cover (Ch. 6: Forests, KM 1; Ch. 5: Land Changes). Forest management adaptation strategies are being developed,^{21,66} including strategies



Supplemental Watering of Livestock During Drought

Figure 24.4: Supplemental watering of livestock in Eastern Oregon during the 2015 drought. Photo credit: Sonia A. Hall.

that address drought-related risks, improve the reliability of forest transportation infrastructure, and protect forest-related ecosystem services (Ch. 6: Forests, KM 3).⁶⁷ Vulnerability assessments and adaptation plans have been completed, or are in progress, for almost every National Forest and Park in the region.⁶⁸

Marine and ocean environments of the Northwest are projected to continue to change gradually in response to climate change, but the full extent of the potential effects on fisheries is not well understood.⁶⁹ In the near term, the fisheries industry can use existing strategies that work within the limits of the natural environment to maintain species abundance, avoid extinction, or increase harvests, such as limited fishing seasons, developing quota systems, and expanding aquaculture (Ch. 9: Oceans, KM 2). In the longer term, particularly as large-scale range shifts occur,

species-dependent management changes and alternative management systems are likely to be needed to maintain fisheries and open up new fisheries opportunities.⁷⁰

Despite the many strategies for reducing risks, adaptive capacity is not uniform across the natural resource sector. Given the heterogeneity across climatic and natural resource industries in the region, it is not likely that productivity gains and losses will be felt equally across the broad diversity in the region.^{71,72}

Emerging Issues

Climate stressors such as increased temperatures, CO₂ fertilization, and precipitation

changes are projected to impact pest, disease, and weed pressures (Ch. 10: Ag & Rural).^{77,78} Improved modeling of climate stressors on yields and crop quality will likely enhance the understanding of climate change effects and inform adaptation options³⁶ and assist in addressing farmers' concerns about future pest and pathogen impacts in the region.^{79,80} Water shortfalls are also likely to continue during drought periods despite adaptation efforts focused on water efficiency and reducing water usage (Ch. 3: Water, KM 1). Western water law assigns a priority date to each right based on seniority, so junior (or more recent) water rights are more likely to be adversely affected under shortage conditions than

Box 24.1: Adaptive Agricultural Approaches in Practice

Farmers and ranchers across the Northwest are creating resilient agro-ecosystems to reduce weather- and climate-related risks while meeting economic, conservation, and adaptation goals. Below are a few examples of these efforts from the region.

- A dryland farmer in Eastern Oregon is implementing flexible cropping methods, which allows the farmer to plant additional crops, instead of leaving the field uncultivated (fallow), when soil moisture conditions allow. By intensifying production and reducing fallow periods, profits have increased while also improving weed management, reducing erosion, and improving soil quality.⁷³
- A vegetable, grain, and livestock farmer in Washington is caring for the soil by using conservation tillage, direct seeding, and double cropping to reduce soil erosion, improve soil health, and increase revenues.⁷⁴
- A cattle ranching family in Washington is using holistic management, a comprehensive approach for ranch decision-making, to reduce environmental risks and improve pasture productivity and profitability.⁷⁵
- Farmers in Oregon's Willamette Valley are using dry farming methods to reduce reliance on irrigation water. This Dry Farming Collaborative is developing and implementing approaches that reduce drought risks during dry summer growing seasons.⁷⁶



Figure 24.5: A farmer in Oregon surveys his no-till field, a practice used to build climate resilience. Photo credit: Sylvia Kantor, Washington State University Extension.

those with senior water rights. More studies would enhance the understanding of which watersheds are at the greatest risk and what, if any, changes could address water limitations in the future. The development of more robust water markets may facilitate adaptation to climate change in the arid and semiarid Pacific Northwest; however, considerable institutional barriers currently prevent their full implementation.⁸¹

Although much is being researched with respect to the effects of climate change on forests and associated ecosystem services, far less has been explored with respect to timber markets. Even then, most of the focus has been on changes in forest productivity overall (e.g., Latta et al. 2010⁴⁷) and less on the consequences of disturbance. Research is absent on the effects of potential increases in supply volatility and the consequences for investment and ultimately on harvest and milling jobs.

Ocean acidification poses a direct threat to shellfish and other calcifying species that are at the base of the food web (Ch. 9: Oceans, KM 1). The prominence of the impact on shellfish farms in the Northwest led to the installation of an ocean monitoring system to track ocean acidity. Although calcium carbonate can be used to increase seawater pH in a hatchery setting,⁸² the same approach cannot be used in the open ocean to prevent shell dissolution.⁸³ The broader food web consequences of decline in calcifying species is an area of active research (Ch. 9: Oceans).

There is a great deal of uncertainty regarding impacts on the economic viability of primarily rural, natural-resource-based economies in the region, particularly the degree to which individual sectors are integrated into global commodity markets, which are likely to vary immensely and be difficult to predict (Ch. 10: Ag & Rural; Ch. 16: International, KM 4).⁵⁰

Key Message 2

Natural World and Cultural Heritage

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

Linkage Between Observed Climate and Regional Risks

The intangible values and aspects of the Northwest's natural environment that support a high quality of life for its residents—wildlife, habitat, and outdoor recreation—are at risk in a changing climate. Tribes and Indigenous communities that rely heavily on the natural environment for their culture and heritage are also at risk.

The Northwest's native wildlife is impacted by climate variability and change *directly* through temperature shifts, water availability, and extreme events, and *indirectly* through loss or fragmentation of habitat.⁸⁴ Changes in climate can alter the balance among competing species or predator–prey relationships (e.g., Wenger et al. 2011⁵²). Three wildlife categories are of principal concern: already sensitive or endangered species, snow-dependent species, and game species. While the first two groups of animals are generally negatively impacted by changes in climate, some game species, such as deer and elk, may thrive. Game species are



First Salmon Ceremony of the Lummi Tribe, Washington

Figure 24.6: Tribes in the Northwest typically honor the first salmon caught in the season through tribal ceremonies. Photo credit: Northwest Indian Fisheries Commission (CC BY 3.0).

of concern not because of their sensitivity to changes in climate and habitat but because of their notable value for recreational hunting and as key cultural resources for tribes. Climate change is also projected to impact First Foods, or foods that tribes have historically cultivated for subsistence, economic, and ceremonial purposes. First Foods vary among tribes but often include berries, roots, water, fish, and local wildlife.^{85,86} Additionally, nearly half of all adults in the region participated in wildlife-related recreation in 2010.⁸⁷ As temperatures increase, the demand for warm-weather outdoor and water-based recreation increases, and visitation rates at local, state, and national parks increase.^{88,89,90} However, boating and other water-based recreation opportunities are likely to decline in the future when summer streamflows and reservoir levels are low. Additionally, popular winter sports and snow-based recreational activities, such as downhill skiing, cross-country skiing, and snowmobiling, have been dramatically impacted by reduced snowfall (see Box 24.7). In low-snowfall years, Washington and Oregon show the highest percentage drop of skier visits, meaning that residents and visitors are losing desirable skiing opportunities.⁹¹

Future Climate Change Relevant to Regional Risks

Wildlife responses to a changing climate are varied and complex (Ch. 7: Ecosystems). Some species, such as cavity nesting birds, will very likely benefit from greater disturbance.^{92,93} Others, particularly snow-dependent species, will likely be unable to persist under climate change.⁹⁴

Game species are expected to have diverse responses to climate change. Longer dry seasons and more pronounced droughts are projected to reduce wetland habitat extent and duration, causing changes in waterfowl movement. Increased fire disturbance, on the other hand, will likely increase shrub cover, a preferred food for deer and elk;⁹⁵ reduced winter snowpack may increase food availability in winter; and warmer temperatures reduce winter stress, all of which would support higher deer and elk populations. The primary climate-related impact on game species will likely come from increases in disease and disease-carrying insects and pests.⁹⁶

Temperature-sensitive bull trout, salmon, and other water-dependent species, such as amphibians, are most vulnerable to increased habitat fragmentation.^{97,98,99} Increased frequency of extreme events such as flooding, debris flows, and landslides are projected to alter habitats and likely cause local extinctions of aquatic species.

Increased winter streamflow and decreased summer flow are projected to threaten salmon spawning,¹⁰⁰ compromising salmon hatchery and reintroduction efforts.¹⁰¹ Projected increases in winter storm intensity will likely lead to higher river flows and increased sediment loading that can bury salmon eggs and reduce salmon survival.¹⁰¹ Rising stream temperatures, ocean acidification, and loss of nearshore and estuarine habitat also increase salmon mortality across all phases of the salmon life cycle.¹⁰²

Shellfish beds are threatened by sea level rise, storm surge, and ocean acidification.^{85,103} Species moving out of traditional hunting, gathering, and fishing areas are projected to impact resource access for many tribes.^{101,104} Increasing wildfire frequency and intensity are changing foraging patterns for elk and deer, and increased prevalence of invasive species and disease will likely diminish both wildlife and foraging for traditional plants, berries, roots, and seeds.¹⁰⁵

In winter, continued decreases in lower-elevation snowpack are projected to impact snow-based recreation.¹⁹ Less snowpack and earlier melting of snowpack will likely result in decreased water availability, reducing the quality, quantity, and availability of water-based recreational opportunities, such as boating, rafting, and fishing.¹⁸

Increased wildfire occurrence is projected to degrade air quality and reduce the opportunity for and enjoyment of all outdoor recreation activities, such as camping, biking, hiking, youth sports, and hunting. Degraded air quality also directly impacts human health and quality of life (see Key Message 4).



Razor Clamming in Washington State

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



Wildfires Affect Outdoor Recreation

Figure 24.8: Wildfires impact outdoor wilderness activities and recreation. Reduced air quality and closed trails and camping grounds are projected to increase as wildfire occurrences increase. Photo credit: Charles Luce.

Recreational ocean fishing opportunities are expected to decline under future climate change scenarios,^{55,56,57} and it is likely that fishery ranges will change.⁵¹ Recreational razor clamming on the coast is also expected to decline due to cumulative effects of ocean acidification, harmful algal blooms, higher temperatures, and habitat degradation (see Figure 24.7 and Key Message 1).

Challenges, Opportunities, and Success Stories for Reducing Risk

Historical and projected changes in amenities affecting the quality of life in the Northwest, such as wildlife, recreation opportunities, and edible plants, form a key challenge for managers of these resources. Informed management, however, can reduce the consequences to those who enjoy and value these resources. Sensitive and endangered plant and animal species currently require special management considerations due to historical habitat changes and past species declines. Management of these species can substantially constrain land and water management options, and the protection of these species will likely become more difficult as suitable habitat is lost.

Game species are already managed. Further management of waterfowl habitat is projected to be important to maintain past hunting levels. If deer and elk populations increase, the pressures they place on plant ecosystems (including riparian systems) may benefit from management beyond traditional harvest levels.

The cultural practice of harvesting and consuming First Foods is integral to tribes and Indigenous health (Ch. 15: Tribes).¹⁰⁶ Many tribes, such as the Confederated Tribes of the Umatilla Indian Reservation are using climate change vulnerability assessments and climate change adaptation plans to alter how First Foods are managed.¹⁰⁷ Tribes can exercise their sovereign rights to manage their

resources in a self-determined and culturally appropriate manner, thereby increasing each tribe's adaptive capacity to respond to climate change impacts on tribal lands, foods, health, and cultures (see Box 24.2).^{85,108,109} Tribes can also increase their adaptive capacity through regional networks, such as the Columbia River Inter-Tribal Fish Commission, that support tribal and Indigenous planning and management (see Key Message 5).

As fisheries become stressed due to climate change, additional management strategies are likely to be needed to maintain fish populations. Strategies that focus on habitat quality and quantity are likely to be the most successful.¹¹⁰

Box 24.2: Pacific Salmon and the Identity and Culture of Northwest Tribes

For most Northwest tribes and Indigenous peoples, salmon fishing is more than a cultural, subsistence, and economic act. The tribes view salmon as an extension of life and an indicator of environmental health, and loss of salmon is equated with the loss of tribal identity and culture. As a testament of the importance of salmon, Julia Davis-Wheeler, a Nez Perce elder, stated: "We need the salmon because it is part of our lives and part of our history. The salmon is a part of us, and we are a part of it. Our children need to be able to feel what it is like to catch and eat salmon. They need to be able to experience that sense of respect that many of us have felt in past years."¹¹¹

Adaptation strategies aimed at restoring and enhancing salmon fisheries can be more successful when traditional knowledge is coupled with modern science.^{112,113} For example, the Nez Perce Tribe used local tribal knowledge to construct "natural" rearing ponds in the Columbia River coupled with introducing wild salmon as broodstock to enhance and restore a culturally significant salmon population.¹⁰⁹ Adaptation and informed management can reduce the consequences to those who enjoy and value these resources.



Figure 24.9: Pacific salmon are essential to most Northwest Tribes' identity and culture. Typically, the first salmon caught is displayed, cleaned, and cooked for the community to share. The skeleton is returned to the water to show respect to the salmon. This photo shows the First Salmon ceremony of the Puyallup Tribe. Pacific salmon—a keystone species in the Northwest—are at risk because of climate change. Economic, social, and cultural values are also at risk if salmon populations continue to decline. Recreational salmon fishing contributes to the quality of life and well-being for many Northwest residents. Photo credit: Matt Nagle, Puyallup Tribal News.

Emerging Issues

Some of the species likely to be affected by climate change are already imperiled by population declines, extirpations, or even extinction as a result of historical changes in habitat and other factors. Climate change adds urgency to addressing existing and emergent challenges. Research is already active in identifying resilient habitats (e.g., Morelli et al. 2016, Luce et al. 2014, Isaak et al. 2016^{114,115,116}) and the means for maintaining and improving habitat resilience in the face of increasing climate and disturbance pressure.¹¹⁷ Habitat modeling that includes projections of natural resource shifts, fragmentation, and identification of new wildlife corridors are projected to be beneficial in supporting land and water management decisions that benefit people, recreation, and the Northwest's varied wildlife.

An institutional network of land, wildlife, and fishery management agencies, tribes, and non-governmental conservation organizations has already successfully reversed negative trends in many fish and wildlife populations caused by other human activities.¹¹⁸ These same groups are exploring methods to improve fish and wildlife resilience in a changing climate. Many habitat improvement activities, a cornerstone of conservation biology, also provide flood mitigation, climate mitigation, adaptation, and ecosystem service co-benefits (Ch. 6: Forests).^{119,120} Despite proactive management and adaptation, it is likely that species not currently listed as endangered could become endangered over the next century, and eventual extinctions are likely, yet challenging to predict.¹²¹

First Foods are an important aspect of tribal and Indigenous health and well-being,¹²² and they can be used as indicators in tribal health assessments and climate adaptation plans.^{112,123}

The loss or decline of First Foods is projected to have cascading physical and mental health impacts for tribes and Indigenous peoples (see Key Message 5) (see also Ch. 15: Tribes, KM 2).^{124,125} However, more research to refine these indicators would better support decision-making (see Box 24.2).^{123,126}

Social indicators link a decline in quality of life in the Northwest to loss of recreational opportunities due to climate change impacts,¹²⁷ but the causal links are not well understood. Additionally, future human migration and population increases may alter the relationship and nature of recreation in the Northwest.¹²⁸ As the population increases, the demand for snow-based recreation is likely to also increase. However, it is not clear how the limited availability of snow-based recreation (for example, a shorter ski season) in the Northwest over the long term can influence interest in snow sports in contrast to alternatives.

Key Message 3

Infrastructure

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

Linkage Between Observed Climate and Regional Risks

Infrastructure plays a critical role in keeping the Northwest's economy running smoothly. Roads, highways, railways, and ports facilitate the movement of people and goods within the region and support valuable import and export markets. Powerlines and substations maintain the reliable supply of electricity to homes, businesses, schools, and hospitals. Dams and reservoirs manage streamflow to minimize flood risks, generate electricity, and provide water supply for irrigation and human consumption. Groundwater wells act as an important water source for agriculture and drinking supplies across much of the region. Levees and seawalls prevent damage to homes and property along rivers and the coast. Culverts manage water flows to protect roadways from flooding and assist with fish passage, including for migrating salmon. Storm water and wastewater systems help minimize flooding, especially in urban areas, and are critical for maintaining water quality. However, most infrastructure is designed for a historical climate, and damage

and disruptions caused by extreme events demonstrate existing infrastructure vulnerabilities that are likely to increase in a changing climate (Ch. 3: Water, KM 2; Ch. 4: Energy, KM 1; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1; Ch. 28: Adaptation, KM 2).

Services provided by infrastructure can be disrupted during extreme weather and climate events, illustrating the sensitivity of these systems to climate variability and change (see Box 24.3). During the 2015–2016 extreme El Niño winter, wave energy along the West Coast was about 50% above normal.¹⁶ Several major storms hit northwestern Oregon, bringing record-breaking rainfall, high winds, and high tides. Tillamook County in Oregon experienced a state of emergency that included major highway and road closures due to flooding, failed culverts, landslides, and sinkholes. Disruptions in transportation networks affected access to food, healthcare, and social services (see Key Message 2) (see also Ch. 12: Transportation, KM 2).¹³⁰ The event highlighted the need to maintain detour routes that were valuable in reaching communities that could become isolated. Wave and storm surge energy

Box 24.3: Tribal Relocation as a Last Resort

The Quinault Indian Nation (QIN), located on the southern coast of Washington's Olympic Peninsula, has experienced repeated flood disasters, as described in the U.S. Climate Resilience Toolkit.¹²⁹ In March 2014, coastal storm surge breached the seawall protecting the town of Taholah, flooding the lower village. In January 2015, heavy rainfall washed out roads, including the Highway 109 bridge, a main access road to and from QIN, and threatened wastewater treatment facilities. With more severe impacts anticipated with climate change, combined with risks from tsunamis, QIN's leadership developed a master plan to relocate the lower village to higher ground. The master plan is considered the first step toward realizing QIN's vision for relocation based on sustainable practices and cultural values. Other Washington tribes have also relocated or begun relocation efforts, including the Hoh Tribe, Quileute Tribe, Makah Tribe, and Shoalwater Bay Tribe. Relocation of a tribe is considered a last resort.



Figure 24.10: Coastal floodwaters inundated the Quinault Indian Nation's lower village of Taholah in March 2014. This event, and continuing concerns about future climate change, prompted the village to begin relocation to higher ground. Photo credit: Michael Cardwell.

along the Pacific Northwest coast is expected to increase with climate change.¹³¹ Continuing efforts to build resilience within the health and transportation sectors in response to flooding hazards will likely help the county weather future storms.¹³⁰

Heavy rainfall can lead to slope instabilities and landslides, which can close roadways and railways. Along the Amtrak Cascades Corridor, more than 900 coastal bluff landslides have blocked the tracks and shut down rail service since 1914, with over 240 disruptions occurring between 2009 and 2013.¹³² Each landslide results in a minimum 48-hour moratorium on commuter rail service. The Washington State Department of Transportation is implementing a Landslide Mitigation Action Plan to proactively address the climatic and other factors contributing to landslide-based rail closures.¹³²

Landslides during winter storms have also closed major Interstates, such as the December 2015 closure of eastbound Interstate 90 near Snoqualmie Pass and the February 2017 closure of westbound Interstate 90 near Issaquah.

Wildfires can result in road and railway closures, reduced water quality in reservoirs, and impacts on the energy sector. The Goodell wildfire in August 2015 forced Seattle City Light to de-energize transmission lines around its Skagit River Hydroelectric Project for several days.¹³³ The combined impact of damages and lost power production totaled nearly \$3 million (in 2015 dollars).¹³⁴ The Eagle Creek fire along the Washington–Oregon border in 2017 led to the closure of Interstate Highway 84 and an adjacent railway, likely increasing shipping costs and creating negative economic impacts on tourism and regional small businesses.¹³⁵

Drought conditions also present challenges for infrastructure, especially water supplies. In Washington, the Department of Ecology allocated almost \$7 million in drought relief funds

in 2015 (in 2015 dollars). Relief grants were used to provide backup or emergency water supplies for irrigation or human consumption where wells were failing or pumping capacity was inadequate.¹³⁶ These small and typically rural systems are relatively more vulnerable to drought impacts when compared to larger urban systems (Ch. 10: Ag & Rural, KM 4).

Future Climate Change Relevant to Regional Risks

Climate change is expected to increase the frequency and/or intensity of many extreme events that affect infrastructure in the Northwest. Available vulnerability assessments for infrastructure show the prominent role that future extremes play. Since much of the existing infrastructure was designed and is managed for an unchanging climate, changes in the frequency and intensity of flooding, drought, wildfire, and heat waves affect the reliability of water, transportation, and energy services.

Hydrologic change will likely be an important driver of future climate stress on infrastructure. As higher temperatures increase the proportion of cold season precipitation falling as rain rather than snow, higher streamflow is projected to occur in many basins, raising flood risks.^{137,138,139,140} An increased risk of landslides is also expected, as more mixed rain and melting snow events occur in low- to mid-elevation mountains.¹⁴¹ Increases in the amount of precipitation falling in heavy rainfall events (including atmospheric rivers)¹⁴² are anticipated to magnify these risks. Along the coast, sea level rise is projected to increase flood risks in low-lying areas and will likely magnify the potential for coastal erosion (Ch. 5: Land Changes) and infrastructure damage during extreme events with high storm surge and wave hazards. By the end of the century, the upper sea level rise projection of 4.3 feet¹⁴³ would impact significant infrastructure investments throughout the Northwest, particularly in the low-lying urban areas of the Puget Sound and Portland (Ch. 8: Coastal).

Multiple Climate Stressors Affect Vulnerable Infrastructure

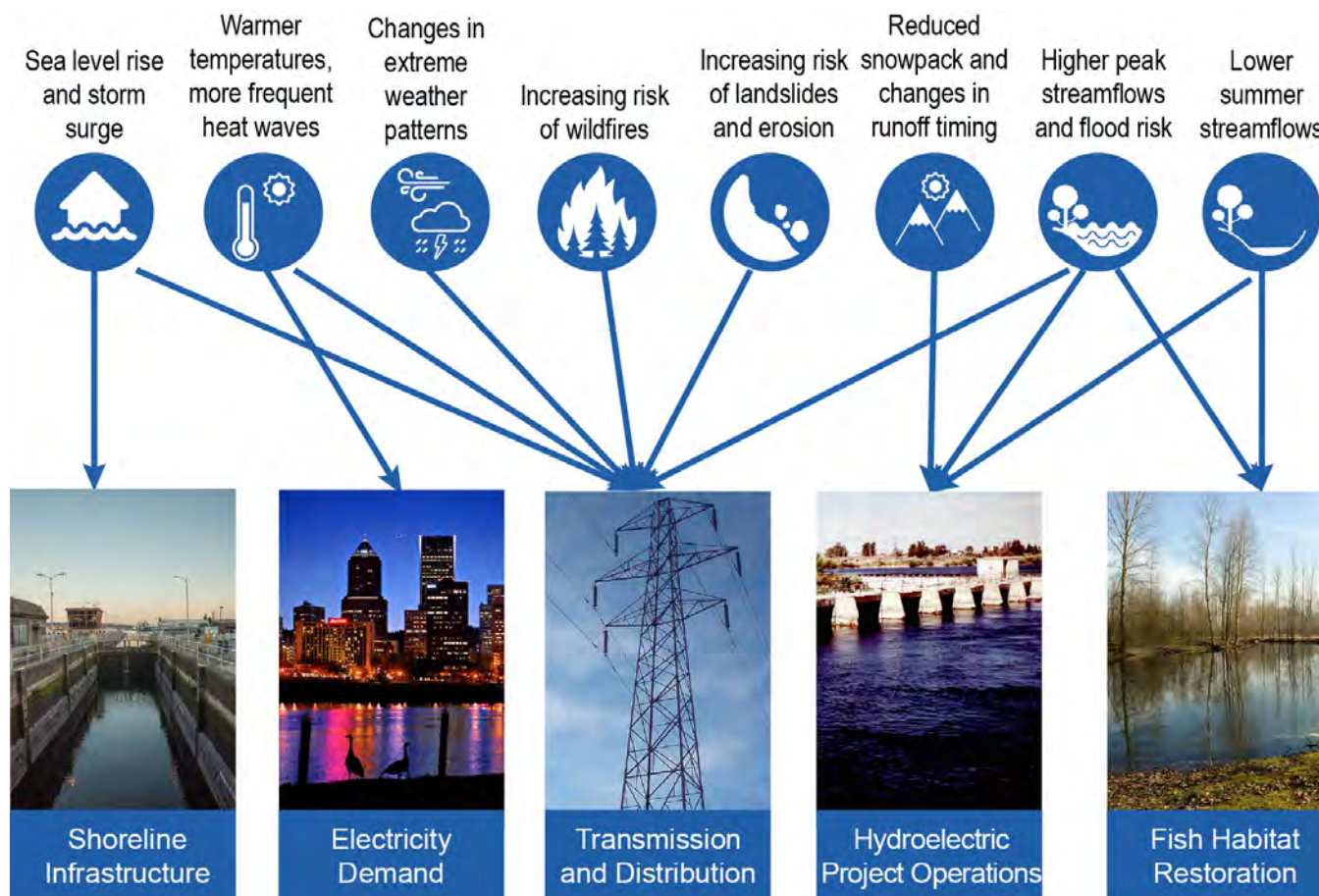


Figure 24.11: Extreme events such as floods, heat waves, wildfires, landslides, and drought play an important role in the vulnerability of infrastructure. The figure, from Seattle City Light's Vulnerability Plan,¹³³ illustrates how the utility's assets, operations, and management goals are affected by a broad range of climate impacts and extreme events. Adaptation strategies to increase the resilience of the energy system must focus on multiple potential risks as well as environmental considerations. Source: adapted from Raymond 2015.¹³³ Photo credits (from left to right): Emmet Anderson (Flickr, [CC BY-NC 2.0](#)), Justin Miller (Flickr, [CC BY-NC 2.0](#)), photojojo3 (Flickr, [CC BY 2.0](#)), U.S. Department of Energy, Rick Swart, Oregon Department of Fish & Wildlife.

Spring and summer streamflows are anticipated to decline in basins that have historically relied on snowmelt, and low flow periods are projected to be more prolonged and more severe. If observed declines in higher elevation precipitation continue,¹⁴⁴ this would exacerbate low streamflow conditions,²⁷ resulting in decreased water supply and reservoir storage. Climate change can affect water quality as well (Ch. 3: Water, KM 1). Higher air temperatures, lower streamflow, and decreases in rainfall are expected to raise summer stream temperatures, making it more difficult to meet water quality standards. In coastal areas, sea level rise will likely lead to saltwater intrusion into groundwater supplies.

Challenges, Opportunities, and Success Stories for Reducing Risk

Anticipated future impacts on infrastructure create opportunities for addressing existing environmental and social goals. For example, actions by the city of Boise, Idaho, to improve water quality are likely to minimize some of the impacts associated with a warmer climate. In Boise, a phosphorous removal facility reduces the amount of phosphorous entering rivers, thereby reducing the need for water treatment facility upgrades¹⁴⁵ and perhaps also preventing downstream algal blooms, which are anticipated to become more common in a warmer climate.

The Northwest has several examples of successful cross-sector collaboration between resource managers and scientists to plan and prepare for climate impacts across multiple sectors (Ch. 17: Complex Systems, KM 3). In Portland and Multnomah County, Oregon, the 2030 Climate Change Preparation Strategy and 2050 Climate Action Plan have incorporated strategies across multiple sectors including water systems, natural and built infrastructure, and human health, with specific social equity considerations woven throughout.^{146,147} For many socially vulnerable populations, limited access to transportation, businesses, and other community resources can inhibit their ability to cope with climate impacts. Addressing these disparities can have the added benefit of bolstering resilience (see Key Message 5). Building and strengthening partnerships across sectors will continue to be important in addressing these complex challenges.

Infrastructure managers in larger urban areas like Seattle and Portland have invested in building climate resilience for their systems (e.g., Vogel et al. 2015, Mauger et al. 2015^{139,148}) (see also Ch. 11: Urban, KM 4), often partnering with researchers to develop tailored climate risk information and adaptation strategies. However, in many parts of the Northwest, especially areas outside urban centers, the lack of redundancy within infrastructure systems will likely be an important factor in limiting adaptive capacity (Ch. 12: Transportation, KM 2; Ch. 10: Ag & Rural, KM 4). Understanding the risks associated with these systems remains a challenge, as impacts could emerge directly from climate events or from the interaction of non-climate and climate stressors (such as equipment failure making a water system more susceptible to subsequent drought). For example, in the Washington Department of Transportation's vulnerability assessment, lifeline roadways that serve as the only means to access communities often emerged as highly vulnerable.¹⁴⁹ Disruptions to these roadways could

cut off communities, preventing supplies or first responders from arriving. The lack of redundancy in transportation networks has also been noted for several of the region's National Parks, contributing to their vulnerability.¹⁴¹ In a similar vein, the Washington Department of Health is examining aspects of groundwater systems that contribute to climate vulnerability. They have found that many groundwater systems are single source and lack any back-up supplies (see Figure 24.12). If supplies are disrupted, either by climate or non-climate stressors, surrounding communities may be forced to transport water to their area or relocate to a place with a more reliable supply (Ch. 3: Water, KM 2).

An additional challenge in addressing future impacts to infrastructure is cost. Projects for replacing, retrofitting, or improving dams, reservoirs, pipelines, culverts, roadways, electrical transmission and distribution systems, and shoreline protection can have costs in the billions (e.g., Wilhere et al. 2017¹⁵⁰).

Managing water in the face of a changing climate also presents an opportunity for transboundary collaboration and coordination. For the Columbia River, projections of future streamflow have been generated for use by U.S. federal agencies, in partnership with Canadian agencies.¹⁵¹ The information about future hydrology can support infrastructure decisions about water supply management, flood risk management, and hydropower production (Ch. 3: Water, KM 3; Ch. 16: International, KM 4).

Emerging Issues

Infrastructure managers are beginning to consolidate planning for the combined risks of sea level rise, flooding, and seismic hazards, as well as tsunami risks that can also arise from a major earthquake event. Going forward, it could be useful to identify strategies that enhance community resilience and emergency

Single-Source Water Systems in Washington

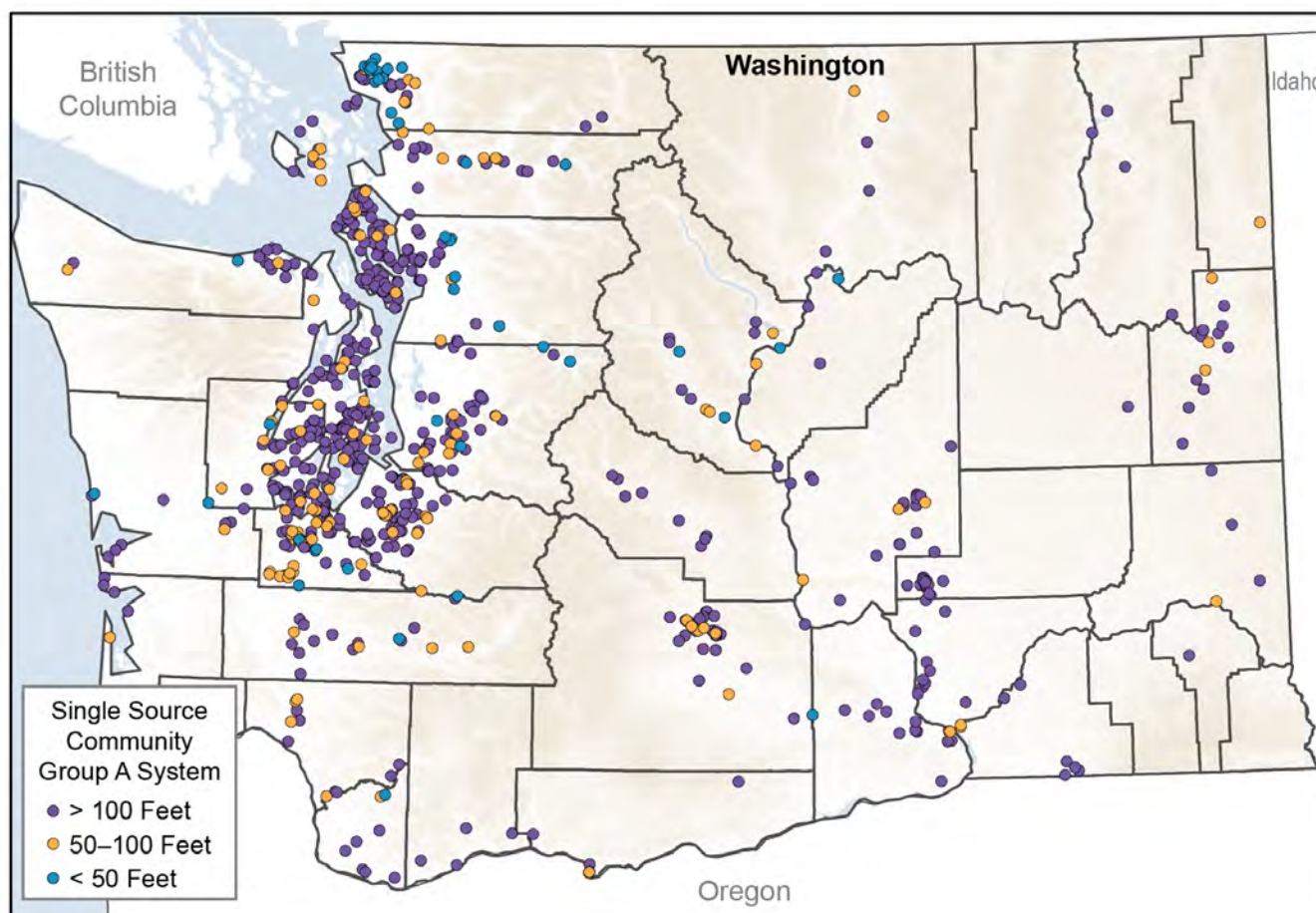


Figure 24.12: The map shows public water systems in Washington that are single source, meaning they lack a backup supply, and service at least 25 people per day or have 15 or more connections. Smaller public water systems exist but are not shown. For operators of single source systems, it will likely be particularly difficult to deal with climate-related disruptions such as flooding, drought, and saltwater intrusion. Approximate well depth is indicated by color; shallower wells (less than 100 feet in blue and orange) are projected to be more vulnerable to impacts, although aquifer type also influences vulnerability. Although similar impacts will likely occur in Oregon and Idaho, the data are not readily available to assess at a statewide level. Source: Washington Department of Health.

response capacity to many types of hazards and potential disruptions.

Infrastructure management is traditionally oriented to protecting assets and services in place. The use of “green” or hybrid “green and gray” infrastructure (e.g., Kittitas County Flood Control Zone District 2015, City of Portland 2010^{152,153}) that utilizes nature-based solutions is emerging as a potential adaptation option.

However, in some locations and for some impacts, it may be more efficient to remove or abandon infrastructure and find alternatives (for example, relocating communities and distributing water or energy systems). The knowledge and experience are just emerging to identify thresholds when such transformative decisions might be appropriate (Ch. 11: Urban, KM 3; Ch. 17: Complex Systems, KM 4).

Key Message 4

Health

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

Linkage Between Climate Change and Regional Risks

Over the last few decades, an increase in climate-related extreme events has led to an increase in the number of emergency room visits and hospital admissions. Warmer and drier conditions during summer have contributed to longer fire seasons.¹⁴⁰ Wildfire smoke can be severe, particularly in communities in the eastern Northwest.¹⁵⁴ Smoke events during 2004–2009 were associated with a 7.2% increase in respiratory hospital admissions among adults over 65 in the western United States.¹⁵⁵ In Boise, Idaho, 7 of the last 10 years have included smoke levels considered “unhealthy for sensitive groups” (including children) for at least a week during the fire season,¹⁵⁴ causing some cancellation of school-related sports activities (Ch. 13: Air Quality, KM 2).

During extreme heat events in King County, Washington, from 1990 to 2010, heat-related hospital admissions were 2% higher and deaths 10% higher than the average for that period,^{156,157} with an increased demand for

emergency medical services for children, outdoor laborers, and the elderly.¹⁵⁸ The state of Oregon has also recorded spikes in heat-related emergency room visits.¹⁵⁹ In particular, agricultural workers are at increased risks for heat-related injuries because they work outside during the summer harvest season.¹⁶⁰

In the last several years, the region has seen an increase in some infectious diseases. An increase in Lyme disease cases is associated with rising temperatures and changing tick habitat.¹⁶¹ The Washington Department of Health's vector surveillance program has observed an earlier onset of West Nile virus-carrying mosquitoes, likely associated with higher temperatures, and an increasing number of human infections, with some resulting in fatalities.¹⁶² Before 1999, cryptococcal infections were limited to the tropics, but *Cryptococcus gatti*, the species that causes these infections, is now established in Northwest soil, with 76 cases occurring in Oregon in 2015.¹⁶³ The Oregon Health Authority recorded spikes in cases of *Salmonella* and *E. coli* during months with extreme heat in 2015.¹⁶³ A large outbreak of Shigellosis (a bacterial diarrheal disease) occurred in late 2015, affecting a large number of homeless people in the Portland Metro region; this outbreak was associated with unusually extreme precipitation.¹⁶⁴

Changes in drought conditions and increased water temperatures have increased the potential for freshwater harmful algal blooms in recreational waters,¹⁶⁵ although there is little capacity among state health departments to monitor and track harmful algal blooms. Toxins from marine harmful algal blooms can accumulate in shellfish, leading to illnesses for those who eat them.¹⁶⁶ In 2015, during the largest harmful algal bloom ever observed off the West Coast from California to Alaska, high levels of domoic acid led to the closure of shellfish harvesting in much of the Northwest (Box 24.7).¹⁶⁷

Children and youth, in general, will likely experience cumulative physical and mental health effects of climate change over their lifetimes¹⁶⁸ due to increased exposure to extreme weather events (such as heat stress, trauma from injury, or displacement) and increased toxic exposures (such as increased ground-level ozone pollution in urban areas or increased risk of drinking water contamination in rural areas). Beginning at the fetal development stage, environmental exposures to air or water pollution can increase the risk of impaired brain development,¹⁶⁹ stillbirth,¹⁷⁰ and preterm births.^{171,172} Infants and children can be disproportionately affected by toxic exposures because they eat, drink, and breathe more in proportion to their body size.¹⁷³ Natural disasters, as well as gradual changes (like changing landscapes and livelihoods) caused by climate stressors, increase the risk of anxiety, depression, and post-traumatic stress disorder (PTSD).¹⁷⁴ Evidence shows that exposure to both pollution and trauma early in life is detrimental to near-term health, and an increasing body of evidence suggests that early-childhood health status influences health and socioeconomic status later in life.^{175,176}

Future Climate Change Relevant to Regional Risks

More frequent wildfires and poor air quality are expected to increase respiratory illnesses in the decades to come (Ch. 13: Air Quality, KM 2). Airborne particulate levels from wildfires are projected to increase 160% by mid-century under a lower scenario (RCP4.5),¹⁷⁷ creating a greater risk of smoke exposure through increasing frequency, length, and intensity of smoke events.¹⁷⁷

Projected increases in ground-level ozone (smog), small particulate matter (PM_{2.5}), and airborne allergens¹⁷⁸ can further complicate respiratory conditions (Ch. 13: Air Quality, KM 1). There is a well-documented link between

exposure to air pollution and risk of heart attack, stroke, some types of cancer, and respiratory diseases,¹⁷⁹ all of which are leading causes of death in the Northwest.¹⁸⁰ The portion of each health condition attributed to air pollution is unknown, but the social and economic costs of these diseases are large. In Oregon, the medical costs associated with heart attacks in 2011 alone were over \$1.1 billion, and those associated with stroke were \$254 million (\$1.2 billion and \$269 million, respectively, in 2015 dollars).¹⁸¹

Increases in average and extreme temperatures are projected to increase the number of heat-related deaths.^{182,183} Mid-century climate in Portland, Oregon, under a mid-high scenario (RCP6.0) may result in more than 80 additional heat-related deaths per year, although this figure does not account for future population growth or possible adaptations.¹⁸⁴

Future extreme precipitation events could increase the risk of exposure to water-related illnesses as the runoff introduces contaminants and pathogens (such as *Cryptosporidium*, *Giardia*, and viruses) into drinking water.¹⁸⁵ In the Puget Sound, under a mid-high emissions scenario (SRES A1B), local atmospheric heating of surface waters is projected to result in 30 more days per year that are favorable to algal blooms and an increased rate of bloom growth.¹⁸⁶

Income loss associated with climate impacts will likely increase the risk of people experiencing food insecurity (see Key Message 1).¹⁸⁷ As an example, in early 2016 a harmful algal bloom impacted the local economy in Long Beach, Washington, which is largely dependent on shellfish, tourism, and service industries. The local Food Bank recorded an almost 25% increase in the number of families requesting assistance in the six months that followed.¹⁸⁸ Climate-driven hardships can also affect mental health, resulting in outcomes ranging from

stress to suicide.¹⁸⁹ Oregon, Washington, and Idaho all rank among the top 10 states in terms of prevalence of mental illness and lowest access to mental health care.¹⁹⁰ Serious mental illness costs the U.S. economy more than \$193 billion in lost earnings each year (\$224 billion in 2015 dollars).¹⁹¹ Tribes and Indigenous peoples face multiple physical and mental health challenges related to climate change, with impacts to subsistence and cultural resources (see Key Messages 2 and 5) (see also Ch. 15: Tribes, KM 2). Some of these health concerns are described in a recent project created by members of the Confederated Tribes of Warm Springs.¹⁹² Tracking climate stressors and training related to climate anxiety and post-disaster trauma is not widespread among the region's health workforce.¹⁹³

Challenges, Opportunities, and Success Stories for Reducing Risk

Existing environmental health risks are expected to be exacerbated by future climate conditions,¹⁸⁷ yet over 95% of local health departments in Oregon reported having only partial-to-minimal ability to identify and address environmental health hazards.¹⁹⁴

With funding from the Centers for Disease Control and Prevention, Oregon has been able to make some headway on assessing climate change vulnerabilities¹⁹⁵ and recently released a statewide climate and health resilience plan.¹⁹⁶ Five local health jurisdictions in Oregon are some of the first in the country to complete local climate and health adaptation plans. Interventions to address community-identified priorities range from providing water testing for domestic well users in drought-prone areas to quantifying the health co-benefits of proposed transportation investments. The Washington Department of Health has also

added a climate program to begin integrating climate considerations into the state's public health system. In addition, the Drinking Water State Revolving Fund has made it possible for water system managers and utilities to apply for low interest loans that support resilience projects. Washington's Marine Biotoxin Program, also housed within the Department of Health, operates an early warning system in partnership with academics, organizations, and citizen scientists to increase the geographic breadth and frequency of sampling for harmful algal blooms that could compromise the safety of shellfish. Public health practitioners in southeastern Idaho have formed a new working group with tribes, universities, local jurisdictions, businesses, and nonprofits to develop strategies for mitigating health impacts of wildfire smoke and water insecurity.

Together, Northwest states have launched the Northwest Climate and Health Network for public health practitioners to share resources and best practices. Idaho, Oregon, and Washington all have syndromic surveillance systems that provide near-real-time data from emergency room visits. These health data have the potential to be layered with climate and environmental data (such as temperature and air quality data), but such analysis has not been carried out on a broad scale.

Incorporating more health and wellness considerations into climate decision-making can increase a community's overall resilience (Ch. 14: Human Health, KM 3). For example, preserving the ecological functions of an area can also promote tribal and Indigenous health, while investing in active transportation and green infrastructure can also improve air quality and increase physical activity.¹⁹⁷

Box 24.4: Healthcare Partnerships That Increase Resilience

A new International Transformational Resilience Coalition (ITRC) has grown out of the Northwest and is engaging cross-sector partners in pilot projects to build psychosocial resilience in some communities. The initiative uses neuroscience and mindfulness to train leaders and organizations on how to cope with, and use, climate-related adversities to catalyze collective adaptation.¹⁹³ Composed of more than 250 mental health, trauma treatment, resilience, climate, and other professionals, the ITRC is working to enhance the ability of organizations and communities to heal, grow, and flourish during economic, social, and environmental stress and adversity.



Figure 24.13: Participants at the 2014 Leaders Self-Care Workshop. Photo Credit: The Resource Innovation Group/International Transformational Resilience Coalition. This caption was revised in June 2019. See Errata for details: <https://nca2018.globalchange.gov/downloads>

Emerging Issues

Communities with higher rates of illness and death often have less adaptive capacity and are more vulnerable to climate stressors.¹⁹⁸ Many people living in the Northwest already struggle to meet basic needs that could serve as protective factors—and these numbers could increase. For example, roughly 1 in 5 children in the region live in a food-insecure household^{199,200,201} and are already at higher risk of poor health outcomes like asthma and diabetes.²⁰² Both the states of Washington and Idaho have had some of the largest increases in homeless populations in the United States, and in 2016, Oregon had the highest rate of unsheltered homeless families with children.²⁰³ People lacking adequate shelter face increased climate risks (such as direct exposure to extreme heat or winter storms) while also having increased vulnerability (such as poorer health and less access to resources).

Displacement and increased migration to the Northwest could place increasing pressures on housing markets, infrastructure, and health and social service systems.¹²⁸ However, the role of climate as a driver for migration to the Northwest is speculative; current population forecasts do not yet account for climate factors.²⁰⁴

Public health leaders in the Northwest are working to modernize health systems to better respond to and prepare for complex and emerging health risks. Coordinated Care Organizations (CCOs) in Oregon, which serve as Medicaid insurance providers, are beginning to invest in certain climate protections for members. For example, some are covering the cost of air conditioning units for patients at risk of heat-related illnesses, ensuring patients can remain in their homes.²⁰⁵ More studies would be needed to fully account for the cost savings associated with these kinds of health-related services.

Key Message 5

Frontline Communities

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

Linkage Between Observed Climate and Regional Risks

Because people care about the place they live, a focus on places serves to highlight the local material and symbolic contexts in which people create their lives and through which those lives derive meaning.^{206,207} This is true for communities across the Northwest whether or not they are on the frontline of dealing with climate change. While there are many types of frontline communities (those communities likely to experience climate impacts first and worst) in the region, this chapter highlights three sets of communities: tribes (Ch. 15: Tribes), farmworkers, and low-income populations in urban and rural (Ch. 10: Ag & Rural) environments.

The effects of climate variability and extreme events are not felt equally across communities in the Northwest. Frontline communities have higher exposures, are more sensitive, and are less able to adapt to climate change for a variety of reasons (Ch. 14: Human Health, KM

1),^{187,208,209} including enhanced occupational exposure,²¹⁰ dependence on natural and cultural resources (Ch. 15: Tribes, KM 1),¹²⁴ fewer economic resources,²⁰⁹ other demographic factors,^{211,212} and gender.²¹³ In addition, frontline communities frequently must overcome cumulative exposures¹²⁵ and intergenerational and historical trauma.^{125,214} It is the interconnected nature of legacy exposure, enhanced exposure, higher sensitivity, and less capability to adapt that intensifies a community's climate vulnerability.^{187,215,216} Climate change can affect the health, well-being, and livelihoods of these communities directly by increasing the risk of acute health impacts, such as physical injury during severe weather,^{189,209} and indirectly through chronic impacts, such as food insecurity or mental health conditions like PTSD (see Key Message 4) (see also Ch. 15: Tribes, KM 2; Ch. 14: Human Health, KM 1).

Future Climate Change Relevant to Regional Risks

Frontline communities generally prioritize meeting existing basic needs, such as shelter, food, and transportation. While climate-related risks vary from community to community, neighborhood to neighborhood, and even person to person, for frontline communities, climate variability, change, and extreme events can exacerbate existing risks, further limiting their ability to meet basic needs.²¹⁷

Northwest tribes directly depend on natural resources, both on and off reservations, and are among the first to experience climate impacts. In the United States, the history of colonization, coupled with ongoing management barriers (such as land fragmentation and limited authority and control over natural resources), has led to many challenges for tribal and Indigenous climate adaptation (see Box 24.5) (see also Ch. 15: Tribes, KM 3).^{124,218} The loss or reduced availability of First Foods (Key Message 2) can have broad physical, cultural,

and spiritual impacts, including diabetes, heart disease, mental health impacts, and loss of cultural identity.^{125,209} This is likely to be coupled with mental health impacts associated with intergenerational and historical trauma, alcohol abuse, suicide, and other impacts (see Key Message 2) (see also Ch. 15: Tribes, KM 2).²⁰⁹

Farmworkers are vital to the region, yet they often earn very low wages and face discrimination and workplace hazards. Farmworkers and their families often deal with both chronic and acute health impacts because of the high cost of healthcare and physically demanding work environments. Overall, farmworkers, who are largely immigrant laborers from Mexico, Central America, and South America, face distinct challenges and are more vulnerable due to structural causes that can lead to exploitation, discrimination, and violence.²¹⁹ Climate change is projected to exacerbate these existing stressors.

While the Northwest is not typically considered a high-risk area for heat-related illness, heat waves (defined as 5-day, 1-in-10-year events) across the country are projected to increase in frequency and intensity.³ In the Northwest, nighttime heat waves (defined as 3-day, 1-in-100-year events) have a greater influence on human health than daytime heat waves²²⁰ and have increased in frequency since 1901.²²¹ These changes are projected to make heat-related illness more common in the future. Farmworkers can be particularly vulnerable to heat-related illness due to occupational exposure (heavy exertion and working outdoors)²¹⁰ and to air quality concerns associated with

wildfires, yet they often do not seek healthcare because of high costs, language barriers, and fear of deportation.²²² Working conditions, as well as cooling and hydration practices, vary across the region.²²³

In urban environments, economically disadvantaged communities and communities of color live in neighborhoods with the greatest exposure to climate and extreme weather events²²⁴ and are, therefore, disproportionately affected by climate stressors.^{225,226} Urban heat islands, worsening air quality,²²⁷ less access to transit, increasing demands for food and energy, and proximity to pollution sites can lead to injury, illness, and loss of life for the urban poor (Key Message 4).^{225,228} For instance, in the Northwest, increased risk of heat-related illnesses and deaths has been associated with socioeconomic status, age, race, and occupation (for example, outdoor labor).^{156,182,229}

Challenges, Opportunities, and Success Stories for Reducing Risk

Many frontline communities are taking actions that begin to address these challenges. Indigenous peoples and Northwest tribes have demonstrated a high degree of resilience by adapting to changing environmental and social conditions for thousands of years (Ch. 15: Tribes).¹²⁴ The strong social networks and connectivity, present in many tribes and Indigenous communities, can reduce vulnerability to climate change (Ch. 15: Tribes, KM 3).²³⁰ Efforts to enhance communication and strengthen network connections between tribes and their partners can be seen across the region.

Box 24.5: Collaborations Can Use Existing Social Cohesion to Build Resilience

Social cohesion, social networks, and other forms of social capital can help communities be more resilient to climate change.²³¹ The Pacific Northwest Tribal Climate Change Network is a regional collaboration aimed at supporting tribal and Indigenous climate resilience by better understanding and communicating the impacts of climate change on Indigenous peoples, tribal sovereignty, and culture. The Network does this by sharing resources such as case studies, tools, and funding opportunities through the Online Tribal Climate Change Guide (<https://tribalclimateguide.uoregon.edu/>); bringing together a diverse group of tribes, agencies, and nonprofit and private sector organizations; and discussing key actions and initiatives that are building resilience among tribes in the region.



Figure 24.14: Social cohesion and social networks can help communities adapt to changing climate conditions. One example is the Pacific Northwest Tribal Climate Change Network (<https://tribalclimate.uoregon.edu/>). The Network provides a forum for tribes to work together and with universities, federal agencies, and private and nonprofit organizations to share information, strengthen connections, and build resilience through events such as the 2017 Tribes and First Nations Climate Summit (<http://atntribes.org/climatechange/events/>) hosted by the Tulalip Tribes and co-sponsored by the Affiliated Tribes of Northwest Indians, the North Pacific Landscape Conservation Cooperative, and the Pacific Northwest Tribal Climate Change Project. Photo credit: Peggy Harris, Affiliated Tribes of Northwest Indians.

Acknowledging the risk of heat-related illness for outdoor workers, the state of Washington issued rules requiring employers to make specific changes to job sites during the summer season (from May 1 through September 30). For temperatures above certain thresholds, the employer is required to provide at least one quart of water per employee per hour, relieve employees from duty if they are showing signs of heat-related illness, and provide training for employees and supervisors about heat-related illness.²³²

Economically disadvantaged populations and communities of color often face multiple

barriers to participating in public processes where decisions about future climate-related investments are made. Organizations representing these frontline communities have found some success prioritizing leadership development through workshops and training that enable new and emerging voices to be heard in more formal policy settings. Engagement has partly been made possible by providing transportation, childcare, meals, and accessibility and by using a relational worldview and trauma-informed approach to community capacity-building. Cities and counties have also made concerted efforts at the policy level to explicitly acknowledge and address race

and social inequities alongside environmental concerns.^{147,228,233,234,235} Example actions include targeting investments in frontline communities and providing job training and employment opportunities that help limit displacement and enhance resilience.¹⁴⁷

Box 24.6: Community Organizations Empower Frontline Communities

Community-based organizations in the Northwest's two most urban centers, Seattle and Portland, have engaged communities of color to assess priorities for building climate resilience. Our People, Our Planet, Our Power²³⁶ and Tyee Khunamokwst: Leading Together²³⁷ both emphasize that any efforts to build climate resilience will be undermined if low-income people and people of color continue to be displaced. Both community-driven efforts indicate strong support for strategies that reduce emissions and simultaneously build community resilience, such as increasing access to active transportation options and installing green infrastructure within under-resourced communities. The cities of Seattle and Portland have made progress in placing equity more centrally in municipal climate planning. The Portland-Multnomah Climate Action through Equity report¹⁴⁷ documents how these efforts led to a more inclusive and accountable climate action plan, and the Seattle Equity & Environment Agenda²²⁸ articulates current disparities and a commitment to ensuring that people most affected by environmental injustices have a strong voice in finding solutions moving forward.

Emerging Issues

There is an emerging understanding of the importance of not only prioritizing climate change preparedness efforts in frontline communities but also involving and empowering these groups in the decision-making and implementation of climate change plans and actions.

The physical and psychological connections people have with natural resources are complex, and additional research would aid understanding of how changing climate conditions are likely to affect not only those natural resources but also the people who depend on them. How intersecting vulnerabilities, driven by a confluence of climatic, social, and economic factors, will compound and accelerate risks in frontline communities is not yet fully understood (Ch. 17: Complex Systems, KM 1). Additional research would help to measure and evaluate how supporting frontline communities in the implementation of community-identified strategies might improve outcomes and increase not only climate resilience but also equity and economic vitality in the Northwest and across the country.

Box 24.7: 2015—A Prelude of What's to Come?

In 2015, the Northwest experienced its warmest year on record.²³⁸ Severe drought, large wildfires, heat waves (on land and in the ocean), and record harmful algal blooms occurred. An exceptionally warm winter led to record-low mountain snowpack across the region as precipitation fell largely as rain instead of snow.⁹ The lack of snowpack and a dry spring led to dry fuel conditions that primed the largest wildfire season recorded in the region.²³⁹

Extreme climate variability provides a preview of what may be commonplace in the future.

In the Northwest, 2015 temperatures were 3.4°F above normal (as compared to the 1970–1999 average),²³⁸ with winter temperatures 6.2°F above normal.²⁴⁰ The warm 2015 winter temperatures are illustrative of conditions that may be considered “normal” by mid-century (higher scenario, RCP8.5) or late century (lower scenario, RCP4.5).¹¹

Winter, spring, and summer precipitation during 2015 for the Northwest were below normal (as compared to the 1970–1999 average) by 25%, 35%, 14%, respectively (NOAA 2017).^{241,242,243} Precipitation from January to June 2015 was the 7th driest on record for the region (4.6 inches below the 20th century average).²⁴⁴ In general, most climate models project increases in future Northwest winter and spring precipitation with decreases in the summer, although some models project increases and others decreases in each season.¹¹ The 2015 spring precipitation deficits are similar to the largest decreases (–34%) in summer precipitation projected for the end of the century (2070–2099) under a higher scenario (RCP8.5).¹¹

Snowpacks in Oregon and Washington in 2015 were the lowest on record at 89% and 70% below average, respectively.⁹ These levels are more extreme than projected under the higher scenario (RCP8.5) by end of century (65% below average).²⁴⁵ However, with continued warming, this type of low snowpack drought is expected more often. For example, the 2015 extreme low snowpack conditions in the McKenzie River Basin (which sits largely in the middle elevation of the Oregon Cascades) could occur on average about once every 12 years under 3.6°F (2.0°C) of warming.²⁴⁶ For each 1.8°F (1°C) of warming, peak snow-water equivalent in the Cascades is expected to decline 22%–30%.²⁴⁷

What happened? How were systems tested? What vulnerabilities were highlighted?

Impacts from the 2015 “snow drought” were widespread, including irrigation shortages, agricultural losses, limited snow- and water-based recreation, drinking water quality concerns, hydropower shortages, and fish die-offs from impaired stream water quality. Many farmers received a reduced allocation of water, and irrigation water rights holders had their water shut off early; senior water rights holders had their water shut off early for the first time ever.²⁴⁸ For example, Treasure Valley farmers in eastern Oregon received only a third of their normal irrigation water because the Owyhee Reservoir received inadequate river inflows to fill the reservoir for the third year in a row.²⁴⁹

Box 24.7: 2015—A Prelude of What's to Come? *continued*

Agricultural-related impacts of the drought were numerous, including damaged crops, reduced yields, altered livestock management, fewer planted crops, and land left idle (for example, 20% of farm acres in Treasure Valley, Oregon, were left idle).²⁴⁸ Estimated agricultural economic losses were between \$633 million and \$773 million in Washington, including losses of over \$7.7 million in blueberries, nearly \$14 million in red raspberries, \$500 million in a selection of 15 crops that make up more than three-quarters of Washington's cultivated acreage, and more than \$33 million in the dairy industry (losses reported in 2015 dollars).²⁵⁰

Low-elevation ski areas struggled to stay open during the 2014–2015 season. Hoodoo Ski Area in the Oregon Cascades had its shortest season in 77 years of operations after closing for the season in mid-January;²⁴⁶ Stevens Pass Mountain Resort in Washington's North Cascades only opened for 87 days, down from an average of 150;²⁵¹ and Silver Mountain Resort in Idaho closed its ski lifts by the end of March, a month earlier than usual.²⁵² Summer water recreation also suffered. Visitation at Detroit Lake, a reservoir in the Cascade foothills, decreased by 26% due to historically low water levels—70 feet (21 meters) below reservoir capacity in July—and unusable boat ramps.^{246,253}

Low summer stream levels and warm waters, which amplified a naturally occurring fish disease, resulted in widespread fish die-offs across the region, including hundreds of thousands of sockeye salmon in the Columbia and Snake River Basins.^{136,248,254} And for the first time ever, Oregon implemented a statewide daily fishing curtailment beginning in July 2015 to limit added stress on the fish from fishing.²⁴⁸

The lack of snowpack in 2015 in concert with extreme spring and summer precipitation deficits led to the most severe wildfire season in the Northwest's recorded history with more than 1.6 million acres burned across Oregon and Washington, incurring more than \$560 million in fire suppression costs (in 2015 dollars).²³⁹ In Oregon, the cost of large fires in 2015 was 344% of the 10-year average of large-fire costs.²⁴⁸ The wildfire season resulted in transmission shutdowns for Seattle City Light during the Goodell Fire (see Key Message 3) and infrastructure damage for Idaho Power Company following the Soda Fire.²⁵⁵ Smoke from the wildfires caused significant air quality and health concerns from late July through September, particularly in eastern Oregon and Washington, Idaho, Colorado, and Canada.^{256,257}

The ocean heat wave referred to as “the Blob” was first detected off the Pacific coast in 2013, and by 2014 it spanned the coast from Alaska to California.¹⁰ In 2015, the largest harmful algal bloom recorded on the West Coast was associated with the Blob. High levels of multiple toxins, including domoic acid and paralytic shellfish toxins, closed a wide range of commercial, recreational, and tribal fisheries, including salmon, shellfish, and Dungeness crab along the entire Northwest coast.^{172,258,259,260}

Box 24.7: 2015—A Prelude of What's to Come? *continued*

Who is doing what to increase resilience? What success stories are there?

The conditions in 2015 tested the capacity of existing systems and provided insights into potential future adaptation priorities. Several actions to increase resilience have already begun across multiple levels of governance. For example, the Oregon Drought Task Force was created to “review the State’s existing drought response tools, identify potential gaps, and make recommendations on tools and information needed to ensure that the State is prepared to respond during a drought in the future.”²⁶¹ Washington assessed the economic impact on agriculture and recommended developing a plan “to assist growers and plan for a future that will include increased incidence of severe weather events such as the 2015 drought.”²⁵⁰

At the onset of the drought, anticipated agricultural losses were much higher than what occurred because of actions at the federal and state levels, and actions implemented by the farmers themselves (Box 24.1).²⁵⁰ This highlights the adaptive capacity of some producers in the agricultural sector (Key Message 1). However, as conditions experienced in 2015 become more regular as a result of climate change, some farms will likely struggle to stay solvent despite adaptation interventions (Ch. 10: Ag & Rural, KM 1).²⁵⁰

After the lack of snow during the previous winter season prevented Mount Ashland Ski Area in southwest Oregon from opening at all, the ski area instituted several adaptation strategies that helped it open and stay open during the 2015 busy winter holidays. Strategies included snow-harvesting and thinning vegetation, among others. Future plans include diversifying the business by creating more summer recreation opportunities, so that the ski area’s revenue depends less on snow-related recreation.²⁴⁹

In the Yakima Basin, irrigators, conservation groups, and state and federal agencies worked together to replenish the diminished tributary flows to bolster the salmon runs and riparian habitat during the drought. Water from the Yakima River was redirected through farm irrigation canals to seven tributaries. Although this further reduced the farmers’ irrigation water, they agreed to continue rerouting water to sustain the fish.²⁶²

Acknowledgments

USGCRP Coordinators

Natalie Bennett

Adaptation and Assessment Analyst

Christopher W. Avery

Senior Manager

Susan Aragon-Long

Senior Scientist

Opening Image Credit

Sawtooth National Forest, Idaho. Photo credit: Mark Lisk/USDA Forest Service.

Traceable Accounts

Process Description

This assessment focuses on different aspects of the interaction between humans, the natural environment, and climate change, including reliance on natural resources for livelihoods, the less tangible values of nature, the built environment, health, and frontline communities. Therefore, the author team required a depth and breadth of expertise that went beyond climate change science and included social science, economics, health, tribes and Indigenous people, frontline communities, and climate adaptation, as well as expertise in agriculture, forestry, hydrology, coastal and ocean dynamics, and ecology. Prospective authors were nominated by their respective agencies, universities, organizations, or peers. All prospective authors were interviewed with respect to the qualifications, and selected authors committed to remain part of the team for the duration of chapter development.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at workshops, weekly teleconferences, and email exchanges. The author team, along with the U.S. Global Change Research Program (USGCRP), also held stakeholder meetings in Portland and Boise to solicit input and receive feedback on the outline and draft content under consideration. A series of breakout groups during the stakeholder meetings provided invaluable feedback that is directly reflected in how the Key Messages were shaped with respect to Northwest values and the intersection between humans, the natural environment, and climate change. The authors also considered inputs and comments submitted by the public, interested stakeholders, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information on the overall report process, see Appendix 1: Process. The author team also engaged in targeted consultations during multiple exchanges with contributing authors for other chapters, who provided additional expertise on subsets of the Traceable Accounts associated with each Key Message.

The climate change projections and scenarios used in this assessment have been widely examined and presented elsewhere^{11,50,263,264} and are not included in this chapter. Instead, this chapter focuses on the impact of those projections on the natural resources sector that supports livelihoods (agriculture, forestry, fisheries, and outdoor recreation industry), the intangible values provided by the natural environment (wildlife, habitat, tribal cultures and well-being, and outdoor recreation experiences), human support systems (built infrastructure and health), and frontline communities (farmworkers, tribes, and economically disadvantaged urban communities). The literature cited in this chapter is largely specific to the Northwest states: Washington, Oregon, and Idaho. In addition, the authors selected a series of case studies that highlight specific impacts, challenges, adaptation strategies and successes, and collaborations that are bringing communities together to build climate resilience. The most significant case study is the 2015 case study (Box 24.7), which cuts across all five Key Messages and highlights how extreme climate variability that is happening now may become more normal in the future, providing important insights that can help inform and prioritize adaptation efforts.

Key Message 1

Natural Resource Economy

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

Description of evidence base

Multiple studies suggest that Northwest natural resource sectors will likely be directly affected by climate change, including increased temperatures, changes in precipitation patterns, and reduced snowpack (see NOAA State Climate Summaries for Oregon, Washington, and Idaho).^{265,266,267} The direct and indirect consequences of these climate drivers are projected to impact regional natural resource sectors in varied ways. In many cases, the secondary and tertiary effects of climatic changes have larger consequences on the natural resource sector, such as increased insect and pest damage to forests,⁴¹ increased wildfire activity,⁸ changes to forage quality and availability for livestock,^{38,39,40} reductions in water availability for irrigation and subsequent impacts to water rights,^{268,269} and increasing temperatures and ocean acidity limiting the viability of existing commercial and recreational fisheries;^{30,55,56,57} lower snowfall is also expected to reduce the economic benefits associated with the recreational skiing industry.^{19,58}

There is good evidence that natural resource managers are attempting to build more resilient production systems in the face of climate change through the adoption of adaptation practices (see Box 24.1), particularly those that build soil resources to increase resilience in the face of more extreme and variable weather; however, in some cases not all adaptation strategies will necessarily lead to broader soil benefits.^{270,271} There is also evidence that adaptive strategies coupled with increased warming will likely shorten the growing season in some parts of the Northwest due to earlier crop maturation, coupled with earlier plantings, leading to lower irrigation demand during low flow periods.³⁴ Forest managers are also incorporating adaptation strategies focused on addressing drought and fire risks as well as broader efforts to protect and maintain key forest ecosystem services.⁶⁷ While adapting to changing ocean conditions is challenging,⁸³ some in the industry are improving monitoring and hatchery practices to reduce risks.⁸² And some in the outdoor recreation industry are looking for ways to benefit from increased temperatures;⁸⁸ for instance, many ski resorts are diversifying their recreational opportunities to take advantage of warmer weather and earlier snowmelt.^{272,273}

Yet, how individual actors respond to changes in climate is a source of uncertainty, particularly if these actions do not reduce climate risks or capitalize on potential benefits as expected.⁶⁴ Additionally, many adaptive actions, at least in the short term, will likely be costly for individual producers to implement.^{37,274}

Major uncertainties

Climate impacts, such as increased temperatures, reduced snowpack, and more variable precipitation and subsequent impacts on pests, disease, fire incidence, and other secondary impacts will very likely indirectly affect livelihoods and the economic viability of natural resource sectors, with more severe impacts to rural, tribal, and Indigenous communities (Ch. 10: Ag & Rural). There is, however, greater uncertainty as to how precisely these impacts are projected to affect natural resource managers' financial security and their subsequent land-use decisions (Ch. 5: Land Changes), as well as other factors important to sustainable livelihoods and community well-being.

This is particularly relevant for key commodities that are integrated with national and international markets that are influenced by multiple factors and are difficult to predict (Ch. 10: Ag & Rural; Ch. 16: International). National and global market dynamics will likely be influenced by broader climate change effects on other natural resource sectors in the United States and across the globe,⁵⁰ while also being impacted by a broad array of factors that include technological developments, laws, regulations and policies affecting trade and subsidies, and security issues. There are instances where the economic consequences will likely be positive, particularly in comparison to other regions in the United States, such as found in the dairy production sector.⁶⁵ The economic impacts to regional fisheries are much less certain as iconic species and industries in the Northwest struggle to maintain viability.^{51,52,53} Although much is being researched with respect to the effects of climate change on forests and associated ecosystem services (e.g., Vose et al. 2016²⁷⁵), far less has been explored with respect to timber markets and attendant infrastructure and processing.

Description of confidence and likelihood

There is *high confidence* that climate change, through reductions in snowpack, increased temperatures, and more variable precipitation, is already affecting the Northwest's diverse natural resource base. There is *high confidence* that these natural resource sectors provide critical economic benefits, particularly for rural, tribal, and Indigenous communities who are more dependent on economic activities associated with natural resource management. There is *high confidence* that climate change will have a large impact on the natural resource sector throughout this century; however, there is *medium confidence* that these impacts will negatively impact rural, tribal, and Indigenous livelihoods, particularly about how projected changes will economically impact specific natural resource sectors due to large uncertainties surrounding global market dynamics that are influenced by climatic and non-climatic factors. It is *very likely* that proactive management efforts will be required to reduce climate risks, yet there is *medium confidence* that these adaptation efforts will adequately reduce negative impacts and promote sector-specific economic benefits.

Key Message 2

Natural World and Cultural Heritage

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

Description of evidence base

Since the Third National Climate Assessment, there have been significant contributions within the literature in relation to climate impacts to Northwest communities, with specific focus on how values and activities, such as recreation, iconic wildlife, management, and tribal and Indigenous cultures, will likely be impacted.

Wildlife are projected to have diverse responses to climate change.^{94,96,121} Droughts, wildfires, reduced snowpack and persistence, shifted flood timing, and heat stress can cause habitat loss or fragmentation⁸⁴ and increase mortality of waterfowl; trout, salmon, and other coldwater fish;^{52,98,276,277,278} amphibians; wolverines; lynxes; and snowshoe hares.⁹⁴ Other species, such as elk and deer, may benefit from future climate conditions.⁹⁶

Multiple studies also demonstrate that climate change impacts will likely affect other iconic, Northwest species. Wildfires will affect berries, roots, and plants;^{85,105} ocean acidification is increasing shellfish mortality, and ocean acidification and warmer ocean temperatures are altering marine food webs;^{279,280,281} and aquatic acidification is affecting salmon physiology and behavior.²⁸² These impacts are projected to have direct negative impacts on traditional Sacred First Foods.^{85,86} Droughts and reduced snowpack will also reduce tribal water supplies.^{101,283} The loss of these First Foods is projected to have cascading physical health impacts, such as diabetes,¹²⁵ and mental health impacts.^{124,125,189,209,214}

Salmon is one of the most iconic Northwest species and important First Foods for Tribes. Salmon are at high risk to climate change because of decreasing summer flows due to changes in seasonal precipitation and reduced snowpack,^{284,285,286,287,288} habitat loss through increasing storm intensity and flooding,^{100,287} physiological and behavioral sensitivity and increasing mortality due to warmer stream and ocean temperatures, and cascading food web effects due to ocean acidification.^{29,281,289,290} These impacts can be amplified due to human-placed impediments (culverts, dams), contaminants, and diseases.^{291,292,293}

There are multiple lines of evidence verifying that reduced snowfall and snowpack in the future will adversely impact winter and snow-based recreation, including a reduction in ski visitation rates.^{19,58,91} This will also adversely affect summer water-based recreation such as boating and rafting,²⁷⁷ although warmer temperatures in the future can increase demand for water-based

recreation and visitations rates to parks.^{88,89,90} Future habitat shifts in marine species⁵¹ and warmer ocean temperatures are projected to lead to declines in opportunities for ocean fishing recreation.^{55,56,57,294} Ocean acidification and harmful algal blooms are also projected to reduce recreational shellfish gathering.⁵⁵ Increased wildfire frequency⁸ will reduce air quality, and some evidence suggests that this can reduce outdoor recreation opportunities and enjoyment. Regional case studies highlight climate impacts to snow-based recreation, ocean fishing, water-based recreation, and decreased air quality.^{28,53,276}

Adaptation and management strategies in response to climate impacts on the natural capital and Northwest heritage are extremely varied across the region. Many tribes have begun managing First Foods and other important cultural resources through climate change vulnerability assessments and adaptation plans that incorporate both traditional knowledge and western science.^{85,107,109,112,113,123} Efforts to manage wildlife, habitats, and species are variable in their approaches to increasing climate resilience, with limited uncertainty in how these strategies can collectively result in increased climate resilience of the region's natural capital.^{54,110,114,117,118,119,120}

Major uncertainties

There is strong evidence to suggest that recreational opportunities are an important quality of the Northwest,⁸⁷ but there is uncertainty around the perceived importance of future recreation opportunities' prioritization in people's quality of life despite the direct reduction of many recreational opportunities.¹²⁷

The effects of climate change on game species are uncertain, with large potential forcing in both directions and a lack of information on which processes will dominate consequences for game species and how managers might be able to effectively adapt to changing climate.

Description of confidence and likelihood

There is *high confidence* that climate change and extreme events have already endangered the well-being of a wide range of wildlife, fish, and plants. There is *very high confidence* that these impacts will directly threaten tribal subsistence and culture and *high confidence* that these impacts will threaten popular recreation activities. Future climate change will *very likely* continue to have adverse impacts on the regional environment. There is *high confidence* that future climate change will have negative impacts on the values, identity, heritage, cultures, and quality of life of the diverse population of Northwest residents. There is *medium confidence* that adaptation and informed management, especially culturally appropriate strategies, will increase the resilience of the region's natural capital.

Key Message 3

Infrastructure

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

Description of evidence base

There is a growing body of evidence suggesting that climate change will likely increase the frequency and/or intensity of extreme events such as flooding, landslides, drought, wildfire, and heat waves.^{27,139,142,295,296,297,298,299,300,301,302} Several investigations have highlighted the vulnerability of water supply, hydropower, and transportation to such changes.^{33,139,303,304,305,306,307}

Infrastructure redundancy is widely accepted as a means to enhance system reliability. Multiple investigations cite the importance of system redundancy for transportation, energy, and water supply.^{136,146,308} Several studies describe the ways that agencies tasked with water, energy, and transportation management are exploring climate change impacts and potential adaptation options.^{133,146,148,151,309,310,311,312,313,314}

Major uncertainties

Many analyses and anecdotal evidence link the risk of infrastructure disruption or failure to extreme events. However, the attribution of specific infrastructure impacts to climate variability or climate change remains a challenge. In many cases, infrastructure is subject to multiple climate and non-climate stressors. Non-climate stressors common to many parts of the region include increases in demand or usage from growing populations and changes in land use or development. In addition, much infrastructure across the region is beyond its useful lifetime or may not be in a state of good repair. These factors typically enhance sensitivity to many types of stressors but add uncertainty when trying to draw a direct connection between climate and infrastructure impacts.

Demographic shifts remain an important uncertainty when assessing future infrastructure impacts as well as the relative importance of certain types of infrastructure. Migration to and within the region can fluctuate on timescales shorter than those of climate change. As people move, the relative importance of different types of infrastructure are likely to change, as are the consequences of impacts.

Lastly, there is considerable uncertainty in quantitatively assessing the role of redundancy in minimizing or managing impacts. Metrics for determining the extent to which networking or emergency/backup systems yield adaptive capacity are not currently available at the regional scale.

Description of confidence and likelihood

There is *very high confidence* in the link between extreme events and infrastructure impacts. Most of the existing vulnerability assessments in this region, as well as those at larger spatial scales, emphasize extreme events as a key driver of past impacts. Most infrastructure is planned and designed to withstand events of a specified frequency and magnitude (for example, the 100-year flood, design storms), underscoring the importance of extreme events to our assumptions about infrastructure reliability and function. There is *high confidence* that rising temperatures, increases in heavy rainfall, and hydrologic changes are projected for the region.^{5,71,139} These changes are anticipated to raise the risk of flooding, landslides, drought, wildfire, and heat waves. There is *medium confidence* about the role of redundancy in determining vulnerability. Although this link has been exhibited in many case studies, quantitative evidence at the local and regional scale has yet to be developed.

Impacts discussed in this chapter (e.g., WSDOT 2014, ODOT and OHA 2016, Withycomb 2017, US Climate Resilience Toolkit 2017^{129,130,132,135}), within other chapters (see Ch. 11: Urban; Ch. 12: Transportation; Ch. 17: Complex Systems; Ch. 28: Adaptation), and elsewhere¹³⁹ highlight the connections among infrastructure systems, or between infrastructure reliability, and access to critical services. In addition, infrastructure systems are faced with a host of non-climate stressors (for example, increased demands from growing population, land-use change). As a result, there is *high confidence* that adaptation efforts designed to address climate impacts across multiple sectors (e.g., Portland-Multnomah County 2014, 2016^{146,147}), as well as those that will yield social environmental co-benefits, will build resilience.

Key Message 4

Health

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

Description of evidence base

Cascading hazards could occur in any season; however, the summer months pose the biggest health challenges. For example, wildfire could occur at the same time as extreme heat and could damage electrical distribution systems, thereby simultaneously exposing people to smoke and high temperatures without the ability to pump water, filter air, or control indoor temperatures. Although some work is being done to prepare, responses to emergency incidents continue to show that there are considerable gaps in our medical and public health systems.³¹⁵ Public health departments are in place to track, monitor, predict, and develop response tactics to disease outbreaks or other health threats. In the case of cascading hazards, the public health system has a

role in communicating risks to the public as well as strategies for self-care and sheltering-in-place during a crisis. Unfortunately, local health departments report inadequate capacity to respond to local climate change-related health threats, mainly due to budget constraints.³¹⁶ Hospitals in the United States routinely operate at or above capacity. Large numbers of emergency rooms are crowded with admitted patients awaiting placement in inpatient beds, and hospitals are diverting more than half a million ambulances per year due to emergency room overcrowding.³¹⁷

Existing environmental health risks are expected to be exacerbated by future climate conditions,¹⁸⁷ yet over 95% of local health departments in Oregon reported having only partial-to-minimal ability to identify and address environmental health hazards.¹⁹⁴ The capacity of our public health systems is largely inadequate and unable to meet basic responsibilities to protect the health and safety of people in the Northwest.^{162,194} Public health leaders from state and local health authorities, state advisory boards, and public health associations have been working together for over five years to develop a plan for rebuilding, modernizing, and funding the region's public health systems.

Socioeconomic income levels can be a predictor of environmental health outcomes in the future.^{187,195} Food systems face continued increases in environmental pressures, with climate change influencing both the quality of food and the ability to distribute it equitably. The capacity to ensure food security in the face of rapidly changing climate conditions will likely be a major determinant of disease burden.³¹⁸

Climate mitigation strategies can in some cases have substantial health co-benefits, with evidence pointing toward active transportation³¹⁹ and green infrastructure improvements.³²⁰ This evidence of health co-benefits provides an additional and immediate rationale for reductions in greenhouse gas emissions beyond that of climate change mitigation alone. Recognition that mitigation strategies can have substantial benefits for both health and climate protection offers the possibility of strategies that are potentially both more cost effective and socially attractive than are those that address these priorities independently.³²¹ The Oregon Health Authority's Climate Smart Strategy Health Impact Assessment found that almost all climate mitigation policies under consideration by the Metro Regional Government could improve health, and that certain policy combinations were more beneficial, namely those that reduced vehicle miles traveled.³²² For example, according to 2009 data available on the National Environmental Public Health Tracking Network, a 10% reduction in PM_{2.5} could prevent more than 400 deaths per year in a highly populated county and about 1,500 deaths every year in the state of California alone. Working across sectors to incorporate a health promotion approach in the design and development of built environment components could mitigate climate change, promote adaptation, and improve public health.³²³

Major uncertainties

Preparing and responding to cascading hazards is complex and involves many organizations outside of the medical and public health systems. There is not a common set of metrics or standards for measuring surge capacity and emergency preparedness across the region.

There is uncertainty in whether domestic migration will place further stress on social safety net systems.

Description of confidence and likelihood

There is *high confidence* that there will be increased hazards and epidemics, which will *very likely* disrupt local economies, food systems, and exacerbate chronic health risks, especially among populations most at risk. There is *high confidence* that these acute hazards will increase due to future climate conditions and will *very likely* increase the demand on organizations and volunteers that respond and form the region's social safety net. There is *medium confidence* that mitigation investments can help counterbalance these risks and *likely* result in health co-benefits for the region.

Key Message 5

Frontline Communities

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

Description of evidence base

Multiple lines of research have shown that the impacts of extreme weather events and climate change depend not only on the climate exposures but also on the sensitivity and adaptive capacity of the communities being exposed to those changes.^{187,230,324,325} For frontline communities in the Northwest, it is the interconnected nature of legacy exposure, enhanced exposure, higher sensitivity, and less capability to adapt that intensifies a community's climate vulnerability.^{187,216}

There are multiple lines of evidence that demonstrate that tribes and Indigenous peoples are particularly vulnerable to climate change. Climate stressors, such as sea level rise, ocean acidification, warmer ocean and stream temperatures, wildfires, or droughts, are projected to disproportionately affect tribal and Indigenous well-being and health,^{106,187,326,327} economies,^{85,124} and cultures.^{105,106} These losses can affect mental health and, in some cases, trigger multigenerational trauma.^{125,189,209,214}

There is limited research on how climate change is projected to impact farmworkers, yet evidence suggests that occupational health concerns, including heat-related concerns^{210,223} and pesticide exposure,³²⁸ could increase, thus exacerbating health and safety concerns among economically and politically marginalized farmworker communities.

Particularly relevant to economically disadvantaged urban populations, extensive work has been done evaluating and analyzing social vulnerability²¹¹ and applying that work to the Northwest.¹⁹⁵ There has also been work completed considering both relative social vulnerability and environmental health data (see WSDOH 2018¹⁶²).

Strong evidence through reports and case studies demonstrates that tribes are active in increasing their resilience through climate change vulnerability assessments and adaptation plans (see <https://>

www.indianaffairs.gov/WhoWeAre/BIA/climatechange/Resources/Tribes/index.htm and <http://tribalclimateguide.uoregon.edu/adaptation-plans> for a list of tribal and Indigenous climate resilience programs, reports, and actions) and through regional networks (for example, Pacific Northwest Tribal Climate Change Network, Affiliated Tribes of Northwest Indians, Northwest Indian Fisheries Commission, Columbia River Inter-Tribal Fish Commission, Point No Point Treaty Council, Upper Snake River Tribes Foundation).

There are also many community organizations across the region focusing on engaging, involving, and empowering frontline communities, including communities of color, immigrants, tribes and Indigenous peoples, and others to design plans and policies that are meaningful (for example, Front and Centered, Got Green, Puget Sound Sage, Coalition of Communities of Color).

Major uncertainties

Actual climate change related vulnerabilities will vary by community and neighborhood.^{187,208} Therefore, the scale of any vulnerability assessment or adaptation plan will matter greatly in assessing the uncertainties.

The secondary and tertiary impacts of changing climate conditions are less well understood. For example, climate change may increase the amount and frequency of pesticides used, and the variety of products used to manage crop diseases, pests, and competing weeds.³²⁸ This is likely to increase farmworker exposure to pesticides and ultimately affect their health and well-being. Further, it is unclear how the altered timing of agricultural management of key crops across the United States (for example, the timing of cherry picking) due to increased temperatures and altered growing seasons may influence the demand for farmworker labor, particularly migrant labor, and how this might impact their livelihoods and occupational health.

There is emerging evidence that there are overlaps between environmental justice concerns and climate change impacts on these communities,^{233,237} and that solutions designed to address one issue can provide effective solutions for the other issue if done well.¹⁴⁷

No systematic catalogue of the actions and efforts of frontline communities in the region to address their climate-related challenges exists. Thus, at this point, most examples of adaptation and climate preparedness are anecdotal, but these examples suggest an increasing trend to link adaptation efforts that simultaneously address both climate and equity concerns. However, this approach is still used sporadically based on the interests, needs, and resources of the communities.

Description of confidence and likelihood

There is *very high confidence* that frontline communities are the first to be affected by the impacts of climate change. Due to their enhanced sensitivity to changing conditions, direct reliance on natural resources, place-based limits, and lack of financial and political capital, it is *very likely* that they will face the biggest climate challenges in the region. However, there is a significant amount of uncertainty in how individuals and individual communities will respond to these changing conditions, and responses will likely differ between states, communities, and even neighborhoods. Thus, it is the complex interaction between the climate exposures and the integrated social-ecological systems as well as the surrounding policy and response environment that will ultimately determine the challenges these communities face.

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Southwest

Federal Coordinating Lead Author**Patrick Gonzalez**

U.S. National Park Service

Chapter Lead**Gregg M. Garfin**

University of Arizona

Chapter Authors**David D. Breshears**

University of Arizona

Keely M. Brooks

Southern Nevada Water Authority

Heidi E. Brown

University of Arizona

Emile H. Elias

U.S. Department of Agriculture

Amrith Gunasekara

California Department of Food and Agriculture

Nancy Huntly

Utah State University

Julie K. Maldonado

Livelihoods Knowledge Exchange Network

Nathan J. Mantua

National Oceanic and Atmospheric Administration

Helene G. Margolis

University of California, Davis

Skyli McAfee

The Nature Conservancy (through 2017)

Beth Rose Middleton

University of California, Davis

Bradley H. Udall

Colorado State University

Review Editor**Cristina Bradatan**

Texas Tech University

Technical Contributors are listed at the end of the chapter.

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Key Message 1

Low water levels in Lake Mead

Water Resources

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

Key Message 2

Ecosystems and Ecosystem Services

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

Key Message 3

The Coast

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

Key Message 4

Indigenous Peoples

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

Key Message 5

Energy

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

Key Message 6

Food

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

Key Message 7

Human Health

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

Executive Summary



The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions,

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

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

Exposure to hotter temperatures and heat waves already leads to heat-associated deaths in Arizona and California. Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution. Given the proportion of the U.S. population in the Southwest region, a

disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.

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

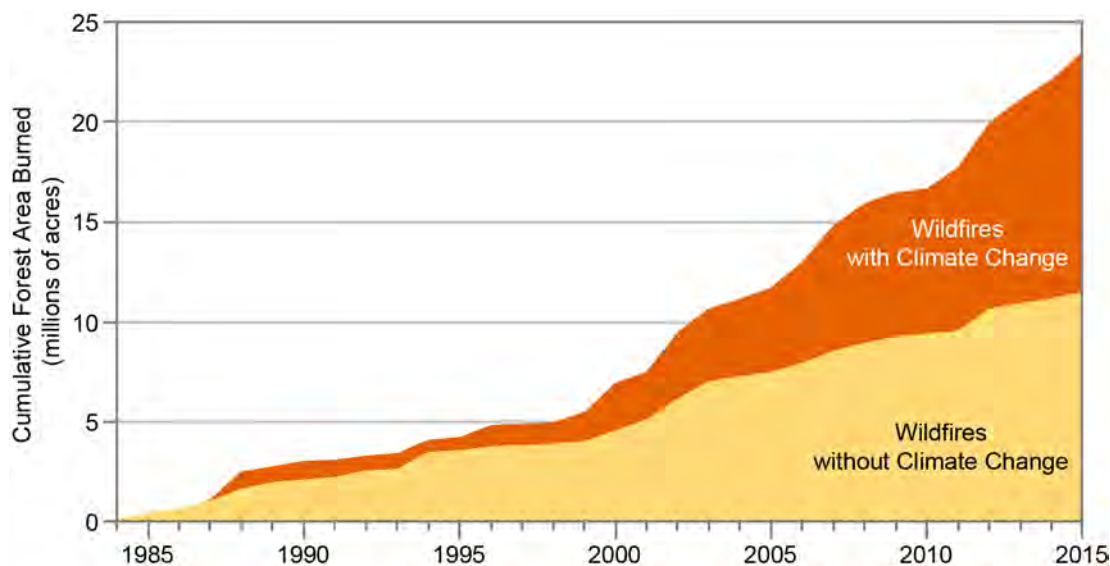
At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016. Climate change caused most of this rise by melting of land ice and thermal expansion of ocean water. Local governments on the California coast are using projections of sea level rise to develop plans to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

Agricultural irrigation accounts for approximately three-quarters of water use in the Southwest region, which grows half of the fruits, vegetables, and nuts and most of the wine grapes, strawberries, and lettuce for the United States. Increasing heat stress during specific phases of the plant life cycle can increase crop failures.

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

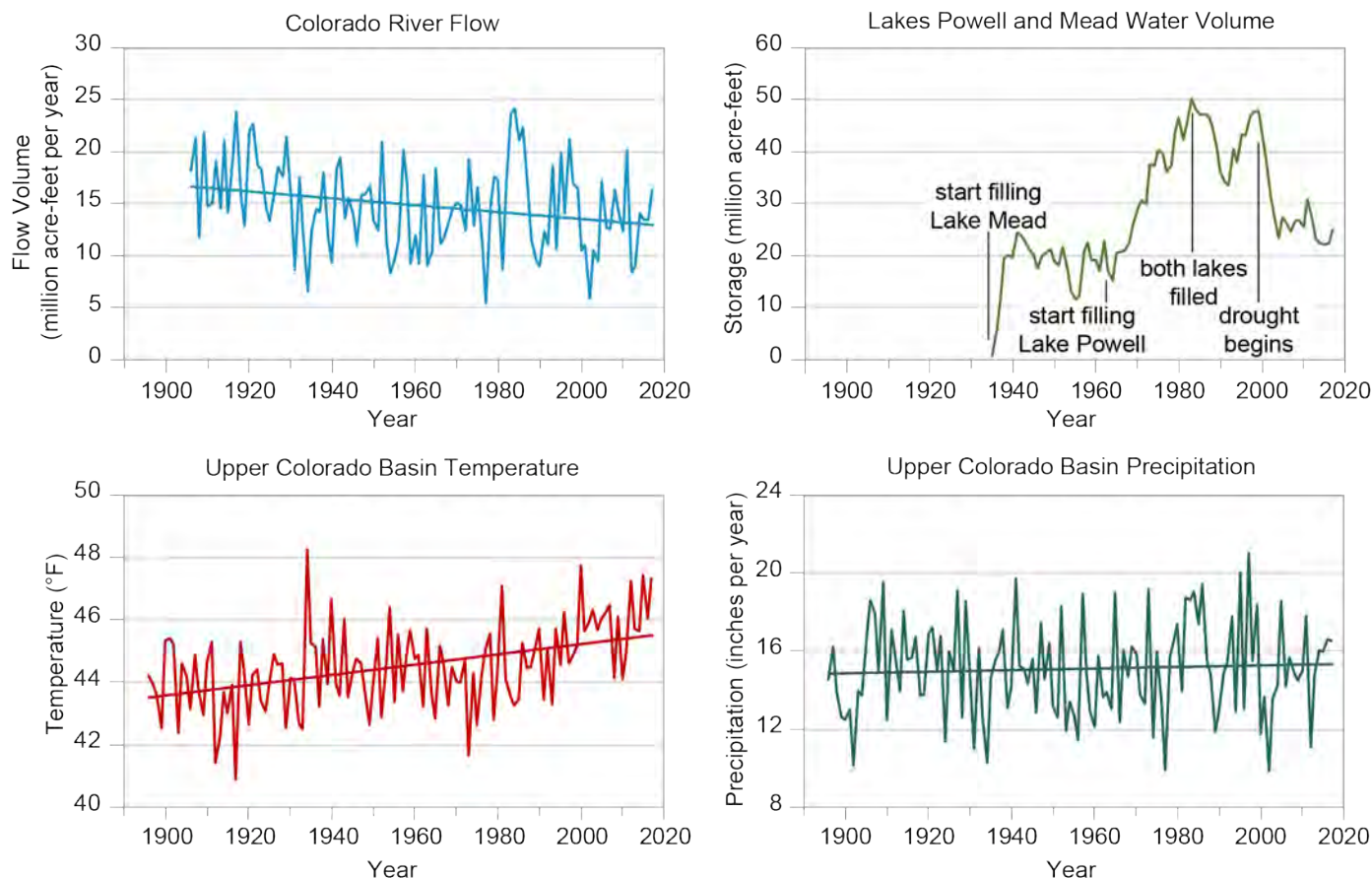
The severe drought in California, intensified by climate change, reduced hydroelectric generation two-thirds from 2011 to 2015. The efficiency of all water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest by 2050. Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest.

Climate Change Has Increased Wildfire



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

Severe Drought Reduces Water Supplies in the Southwest



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

Background

The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Arizona, California, Colorado, New Mexico, Nevada, and Utah occupy one-fifth of U.S. land area, extending across globally unique ecosystems from the Sonoran Desert to the Sierra Nevada to the Pacific Coast. The region is home to 60 million people, with 9 out of 10 living in urban areas and the total population growing 30% faster than the national average.¹ The Nation depends on the region for more than half of its specialty crops such as fruits, nuts, and vegetables.² The Southwest also drives the U.S. technology sector, with more than 80% of the country's technology capitalization located in California.³

Ecosystems in the Southwest gradually transform from deserts and grasslands in hotter and lower elevations in the south to forests and alpine meadows in cooler, higher elevations in the north. Natural and human-caused wildfire shapes the forests and shrublands that cover one-quarter and one-half of the region, respectively.⁴ To conserve habitat for plants and wildlife and supply clean water, timber, recreation, and other services for people, the U.S. Government manages national parks and other public lands covering half of the Southwest region.⁵ Climate change is altering ecosystems and their services through major vegetation shifts²¹³ and increases in the area burned by wildfire.⁷

The California coast extends 3,400 miles (5,500 km),⁸ with 200,000 people living 3 feet (0.9 m) or less above sea level.⁹ The seaports of Long Beach and Oakland, several international airports, many homes, and high-value infrastructure lie along the coast. In addition, much of the Sacramento–San Joaquin River

Delta is near sea level. California has the most valuable ocean-based economy in the country, employing over half a million people and generating \$20 billion in wages and \$42 billion in economic production in 2014.¹⁰ Coastal wetlands buffer against storms, protect water quality, provide habitat for plants and wildlife, and supply nutrients to fisheries. Sea level rise, storm surges, ocean warming, and ocean acidification are altering the coastal shoreline and ecosystems.

Water resources can be scarce because of the arid conditions of much of the Southwest and the large water demands of agriculture, energy, and cities. Winter snowpack in the Rocky Mountains, Sierra Nevada, and other mountain ranges provides a major portion of the surface water on which the region depends. Spring snowmelt flows into the Colorado, Rio Grande, Sacramento, and other major rivers, where dams capture the flow in reservoirs and canals and pipelines transport the water long distances. Complex water laws govern allocation among states, tribes, cities, ecosystems, energy generators, farms, and fisheries, and between the United States and Mexico. Water supplies change with year-to-year variability in precipitation and water use, but increased evapotranspiration due to higher temperatures reduces the effectiveness of precipitation in replenishing soil moisture and surface water.^{11,12,13,14}

Agricultural irrigation accounts for nearly three-quarters of water use in the Southwest region,^{15,16} which grows half of the fruits, vegetables, and nuts² and most of the wine grapes, strawberries, and lettuce¹⁷ for the United States. Consequently, drought and competing water demands in this region pose a major risk for agriculture and food security in the country. Through production and trade networks, impacts to regional crop production

can propagate nationally and internationally (see Ch. 16: International, KM 1)¹⁸

Parts of the Southwest reach the hottest temperatures on Earth, with the world record high of 134°F (57°C) recorded in Death Valley National Park, California¹⁹ and daily maximum temperatures across much of the region regularly exceeding 98°F (35°C) during summer.²⁰ Greenhouse gases emitted from human activities have increased global average temperature since 1880²¹ and caused detectable warming in the western United States since 1901.²² The average annual temperature of the Southwest increased 1.6°F (0.9°C) between 1901 and 2016 (Figure 25.1).²³ Moreover, the region recorded more warm nights and fewer cold nights between 1990 and 2016),²⁴ including an increase of 4.1°F (2.3°C) for the coldest day of the year. Parts of the Southwest recorded the highest temperatures since 1895, in 2012,²⁵ 2014,²⁶ 2015,²⁷ 2016,²⁸ and 2017.²⁹

Extreme heat episodes in much of the region disproportionately threaten the health and well-being of individuals and populations who are especially vulnerable (Ch. 14: Human Health, KM 1).³⁰ Vulnerability arises from numerous factors individually or in combination, including physical susceptibility (for example, young children and older adults), excessive exposure to heat (such as during heat waves), and socio-economic factors that influence susceptibility and exposure (for example, hot and poorly ventilated homes or lack of access to public emergency cooling centers).^{31,32,33} Communicable diseases, ground-level ozone air pollution, dust storms, and allergens can combine with temperature and precipitation extremes to generate multiple disease burdens (an indicator of the impact of a health problem).

Episodes of extreme heat can affect transportation by reducing the ability of commercial airlines to gain sufficient lift for takeoff at major regional airports (Ch. 12: Transportation, KM 1).³⁴

Temperature Has Increased Across the Southwest

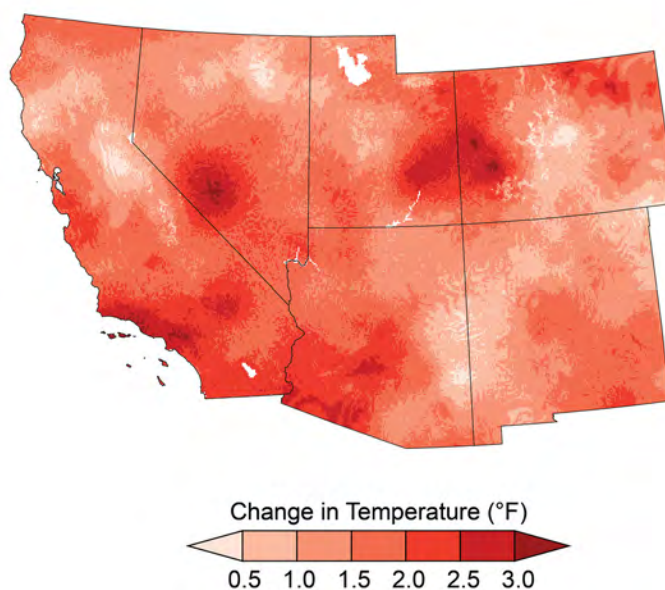


Figure 25.1: Temperatures increased across almost all of the Southwest region from 1901 to 2016, with the greatest increases in southern California and western Colorado.²³ This map shows the difference between 1986–2016 average temperature and 1901–1960 average temperature.²³ Source: adapted from Vose et al. 2017.²³

Native Americans are among the most at risk from climate change, often experiencing the worst effects because of higher exposure, higher sensitivity, and lower adaptive capacity for historical, socioeconomic, and ecological reasons. With one and a half million Native Americans,³⁵ 182 federally recognized tribes,³⁶ and many state-recognized and other non-federally recognized tribes, the Southwest has the largest population of Indigenous peoples in the country. Over the last five centuries, many Indigenous peoples in the Southwest have either been forcibly restricted to lands with limited water and resources^{37,38,39} or struggled to get their federally reserved water rights recognized by other users.⁴⁰ Climate change exacerbates this historical legacy because the sovereign lands on which many Indigenous peoples live are becoming increasingly dry.

Further, climate change affects traditional plant and animal species, sacred places, traditional building materials, and other material cultural heritage. The physical, mental, emotional, and spiritual health and overall well-being of Indigenous peoples rely on these vulnerable species and materials for their livelihoods, subsistence, cultural practices, ceremonies, and traditions.^{41,42,43,44}

In parts of the region, hotter temperatures have already contributed to reductions of seasonal maximum snowpack and its water content over the past 30–65 years,^{45,46,47,48,49} partially attributed to human-caused climate change.^{45,46,48,49} Increased temperatures most strongly affect snowpack water content, snow-melt timing, and the fraction of precipitation falling as snow.^{48,50,51,52,53,54}

The increase in heat and reduction of snow under climate change have amplified recent hydrological droughts (severe shortages of water) in California,^{14,55,56,57,58} the Colorado River Basin,^{12,13,59} and the Rio Grande.^{45,60} Snow

droughts can arise from a lack of precipitation (dry snow drought), temperatures that are too warm for snow (warm snow drought), or a combination of the two.^{48,51}

Periods of low precipitation from natural variations in the climate system are the primary cause of major hydrological droughts in the Southwest region,^{61,62,63,64,65,66,67,68} with increasing temperatures from climate change amplifying recent hydrological droughts, particularly in California and the upper Colorado River Basin.^{12,13,14,56,57,59}

Under the higher scenario (RCP8.5), climate models project an 8.6°F (4.8°C) increase in Southwest regional annual average temperature by 2100.²³ Southern parts of the region could get up to 45 more days each year with maximum temperatures of 90°F (32°C) or higher.²³ Projected hotter temperatures increase probabilities of decadal to multi-decadal megadroughts,^{61,62,69,70} which are persistent droughts lasting longer than a decade,⁶⁹ even when precipitation increases. Under the higher scenario (RCP8.5), much of the mountain area in California with winters currently dominated by snow would begin to receive more precipitation as rain and then only rain by 2050.⁷¹ Colder and higher areas in the intermountain West would also receive more rain in the fall and spring but continue to receive snow in the winter at the highest elevations.⁷¹

Increases in temperature would also contribute to aridification (a potentially permanent change to a drier environment) in much of the Southwest, through increased evapotranspiration,^{69,70,72,73} lower soil moisture,⁷⁴ reduced snow cover,^{71,75,76,77} earlier and slower snowmelt,⁷⁵ and changes in the timing and efficiency of snowmelt and runoff.^{50,54,75,76,78,79} Some research indicates increasing frequency of dry high-pressure weather systems associated with changes in Northern Hemisphere

atmospheric circulation.^{80,81} These changes would tend to increase the duration and severity of droughts^{67,74} and generate an overall drier regional climate.^{69,70,72}

Climate models project an increase in the frequency of heavy downpours, especially through atmospheric rivers,^{74,82} which are narrow bands of highly concentrated storms that move in from the Pacific Ocean. A series of strong atmospheric rivers caused extreme flooding in California in 2016 and 2017. Under the higher scenario (RCP8.5), models project increases in the frequency and intensity of atmospheric rivers.^{83,84,85,86} Climate models also project an increase in daily extreme summer precipitation in the Southwest region, based on projected increases in water vapor resulting from higher temperatures.^{20,87,88} Projections of summer total precipitation are uncertain, with average projected totals not differing substantially from what would be expected due to natural variations in climate.⁸⁸

The Southwest generates one-eighth of U.S. energy, with hydropower, solar, wind, and other renewable sources supplying one-fifth of regional energy generation.⁸⁹ By installing so much renewable energy, the Southwest has lowered its per capita and per dollar greenhouse gas emissions below the U.S. average.⁹⁰ Climate change can, however, decrease hydropower and fossil fuel energy generation.⁹¹ California has enacted mandatory greenhouse gas emissions reductions,⁹² and Arizona, California, Colorado, Nevada, and New Mexico have passed renewable portfolio standards to reduce fossil fuel dependence and greenhouse gas emissions.⁹³

What Is New in the Fourth National Climate Assessment

This chapter builds on assessments of climate change in the Southwest region from the three previous U.S. National Climate Assessments.^{94,95,96} Each assessment has consistently identified drought, water shortages, and loss of ecosystem integrity as major challenges that the Southwest confronts under climate change. This chapter further examines interconnections among water, ecosystems, the coast, food, and human health and adds new Key Messages concerning energy and Indigenous peoples.

Since the last assessment, published field research has provided even stronger detection of hydrological drought, tree death, wildfire increases, sea level rise, and warming, oxygen loss, and acidification of the ocean that have been statistically different from natural variation, with much of the attribution pointing to human-caused climate change. In addition, new research has provided published information on future vulnerabilities and risks from climate change, including floods, food insecurity, effects on the natural and cultural resources that sustain Indigenous peoples, illnesses due to the combination of heat with air pollution, harm to mental health, post-wildfire effects on ecosystems and infrastructure, and reductions of hydropower and fossil fuel electricity generation.

This chapter highlights many of the increasing number of actions that local governments and organizations have been taking in response to historical impacts of climate change and to reduce future risks (Figure 25.2). Some examples include voluntary water conservation and management in California and the Colorado River Basin, restoring cultural fire management in California, and rooftop solar policies in California, Colorado, and Nevada. Many state and local governments have issued climate change assessments and action plans.

Actions Responding to Climate Change Impacts and Vulnerabilities

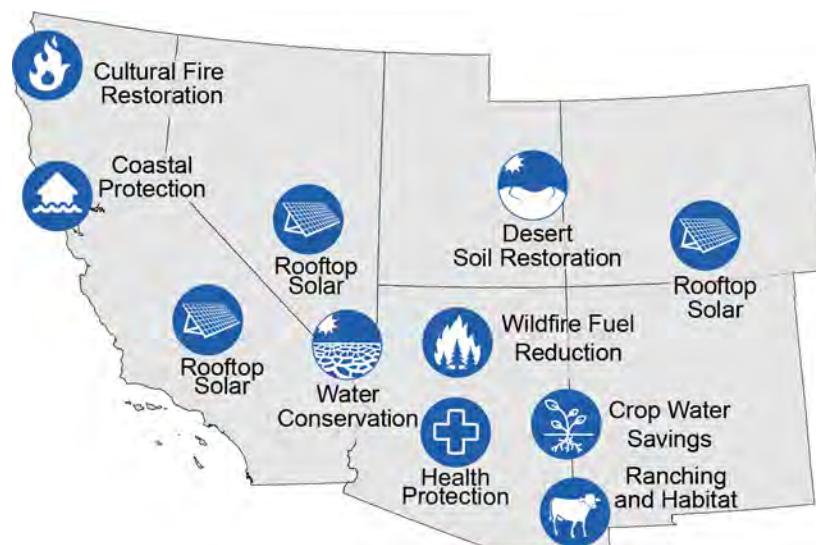


Figure 25.2: These examples illustrate actions that people, communities, and governments are taking in response to past impacts of climate change and future vulnerabilities. **Coastal protection:** In response to sea level rise and storm surge in San Francisco Bay, federal, state, and local agencies, supported by voter-approved funds, are restoring coastal habitats and levees to protect cities from flooding. **Crop water savings:** The risk of reduced food production increases as climate change intensifies drought. In the Gila River Basin, local government agencies have lined 15 miles (24 km) of irrigation canals to reduce seepage from the canals, saving enough water to irrigate approximately 8,500 acres (3,400 hectares) of alfalfa and other crops each year. **Cultural fire restoration:** Reintroduction of cultural burning by the Yurok Tribe in northern California reduces wildfire risks and protects public and tribal trust resources. **Desert soil restoration:** In Utah, transplanting native and drought-resistant microbial communities improves soil fertility and guards against erosion. **Health protection:** To reduce heat-associated injury and deaths on Arizona trails, the City of Phoenix and Arizona tourism organizations developed a campaign “Take a Hike. Do it Right.” Signs at trailheads and on websites remind hikers to bring water, stay hydrated, and stay aware of environmental conditions. **Ranching and habitat:** The Malpai Borderlands Group in Arizona and New Mexico integrates native plant and wildlife conservation into private ranching. **Rooftop solar:** The state governments of California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, which reduces greenhouse gas emissions, improves reliability of the electricity generation system, and creates local small businesses and new jobs. **Water conservation:** Drought in the Colorado River Basin has reduced the volume of water in both Lake Mead and Lake Powell by over half. The United States, Mexico, and state governments have mobilized users to conserve water, keeping the lake above a critical level. **Wildfire fuel reduction:** In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to fund reduction of fire fuels in forests around the town. Source: National Park Service.

Key Message 1

Water Resources

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

Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. In California, the higher temperatures intensified the 2011–2016 drought,^{14,56,97,98,99} which had been initiated by years of low precipitation,^{57,58} causing water shortages to ecosystems, cities, farms, and energy generators. In addition, above-freezing temperatures through the winter of 2014–2015 led to the lowest snowpack in California (referred to as a warm snow drought) on record.^{47,55,98,100} Through increased temperature, climate change may have accounted for one-tenth to one-fifth of the reduced soil moisture from 2012 to 2014 during

the recent California drought.¹⁴ In the ongoing Colorado River Basin drought, high temperatures due mainly to climate change have contributed to lower runoff^{12,59} and to 17%–50% of the record-setting streamflow reductions between 2000 and 2014 (Figure 25.3).¹³ In the Rio Grande, higher temperatures have been linked to declining runoff efficiency⁶⁰ and reductions in snowpack.⁴⁵

Increased temperatures, especially the earlier occurrence of spring warmth,¹⁰¹ have significantly altered the water cycle in the Southwest region. These changes include decreases in snowpack and its water content,^{46,47,48,49,102} earlier peak of snow-fed streamflow,¹⁰³ and increases in the proportion of rain to snow.^{49,103} These changes, attributed mainly to climate change,^{49,103} exacerbate hydrological drought.

With continued greenhouse gas emissions, higher temperatures would cause more frequent and severe droughts in the Southwest.^{11,56,62,65,80} This would also lead to drier future conditions for the region.^{70,74} Higher temperatures sharply increase the risk of megadroughts—dry periods lasting 10 years or more.^{61,62,65} Under the higher scenario (RCP8.5), models project annual declines of river flow in southern basins (the Rio Grande and the lower Colorado River) and either no change or modest increases in northern basins (northern California and the upper Colorado River).^{78,104,105,106,107} Snowpack supplies a major portion of water in the Southwest, but with continued emissions, models project substantial reductions in snowpack, less snow and more rain, shorter snowfall seasons, earlier runoff,^{55,71,78,79,108,109} and warmer late-season stream temperatures.¹¹⁰ Fewer days with precipitation would lead to increased year-to-year variability.^{111,112,113} Substantial increases in precipitation would be needed to overcome temperature-induced decreases in river flow.¹³ The combination of reduced river flows in California and the

Colorado River Basin and increasing population in southern California, which imports most of its water, would increase the probability of future water shortages.¹¹⁴

In response to the recent California drought, the state government implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices such as watering during or after a rainfall, hosing off sidewalks, and irrigating ornamental turf on public street medians.¹¹⁵ As a result, the people of the state reduced water use 25% from 2014 to 2017, when abundant rains allowed the state to lift many restrictions while continuing to promote water conservation as a way of life.¹¹⁶

The Southern Nevada Water Authority used similar measures to reduce water use per person 38% from 2002 to 2016.¹¹⁷ Water utilities in the Colorado Front Range also used similar conservation practices to reduce water use more than 20% in the early 2000s.¹¹⁸ While many southwestern cities have reduced total and per-person water use since the 1990s despite growing populations,¹¹⁹ ongoing drought has increased competition for reliable water supplies in many locations. In parts of Colorado, Nevada, and Utah, population growth has prompted proposals for new water diversions and transfers from agriculture. While desalination of seawater and brackish water has been proposed as a partial solution to water scarcity, its high energy requirement creates greenhouse gas emissions and its capital costs are high.¹⁵

Atmospheric rivers, which have caused many large floods in California,¹²⁰ may increase in severity and frequency under climate change.^{82,83,107,121,122,123,124} In the winter of 2016–2017, a series of strong atmospheric rivers generated high runoff in northern California and filled reservoirs. At Oroville

Dam, high flows eroded the structurally flawed emergency spillway, caused costly damage, and led to the preventive evacuation of people living downstream. In addition to the immediate threat to human life and property, this incident revealed two water supply risks. First, summer water supplies are reduced when protective flood control releases of water from reservoirs are necessary in the spring.¹⁰⁸ Second, several studies have concluded that deteriorating dams, spillways, and other infrastructure require substantial maintenance and repair.^{125,126} In U.S.–Mexico border cities with chronic urban storm water and pollutant runoff problems¹²⁷ and populations vulnerable to flooding,^{127,128} projected increases in heavy precipitation⁸⁸ would increase risks of floods.

Wet periods present a water resource opportunity because increased infiltration from the surface

into the ground recharges groundwater aquifers. Groundwater was critical for farmers during the California drought, especially for fruit and nut trees and grapevines.^{129,130,131} Overdraft of groundwater, however, caused land subsidence (sinking), which can permanently reduce groundwater storage capacity and damage infrastructure as the ground deforms.¹³²

In light of projected future changes in the hydrologic cycle, water resource planners and scientists are testing new techniques to combine results from multiple climate and hydrology models, downscale climate model output to finer geographic scales, calculate changing water demands, and use forecasts for flood control.^{133,134,135,136} Integrating data from satellites, climate and hydrology models, and field observations remains difficult with existing water management tools, methods, and legal requirements.

Box 25.1: Collaborative Management of Colorado River Water

Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume,^{137,138,139} a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture (Figure 25.3). This is the lowest level since the filling of the reservoir in 1936.¹³⁹ The reduction of Lake Mead increases the risk of water shortages across much of the Southwest and reduces energy generation at the Hoover Dam hydroelectric plant at the reservoir outlet. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. The parties have taken four key actions:

1. Arizona, California, and Nevada agreed in 2007, with Mexico joining in 2012, to allow users to store water in Lake Mead for later years, rather than being forced to use it immediately or lose their rights.¹⁴⁰
2. The United States and Mexico agreed in 2014 to release water for eight weeks to re-water the Colorado River Delta in Mexico in order to improve wildlife habitat and to conduct research on environmental restoration.¹⁴¹



Hydrological drought in Lake Mead, Nevada, on March 10, 2014. Photo credit: U.S. Bureau of Reclamation.

Box 25.1: Collaborative Management of Colorado River Water, *continued*

3. The water agencies of Denver, Las Vegas, Los Angeles, and Phoenix and the U.S. Bureau of Reclamation in 2015 set up the Colorado River System Conservation Pilot Program, a fund for local water conservation projects. A second phase extended conservation projects to all of the Colorado River Basin.
4. Mexico agreed in 2017 to absorb a share of water shortages if Lake Mead fell below a specific elevation. The agreement continues Mexico's right to bank unused water in Lake Mead for future use. With financial and other U.S. assistance, Mexico will pursue water conservation projects and environmental restoration within the Colorado River Delta.

Currently, stakeholders are engaged in drought contingency planning for multiple climate futures, implementing management strategies that make sense for the range of climate futures, and preserving options when possible.¹⁴²

Severe Drought Reduces Water Supplies in the Southwest

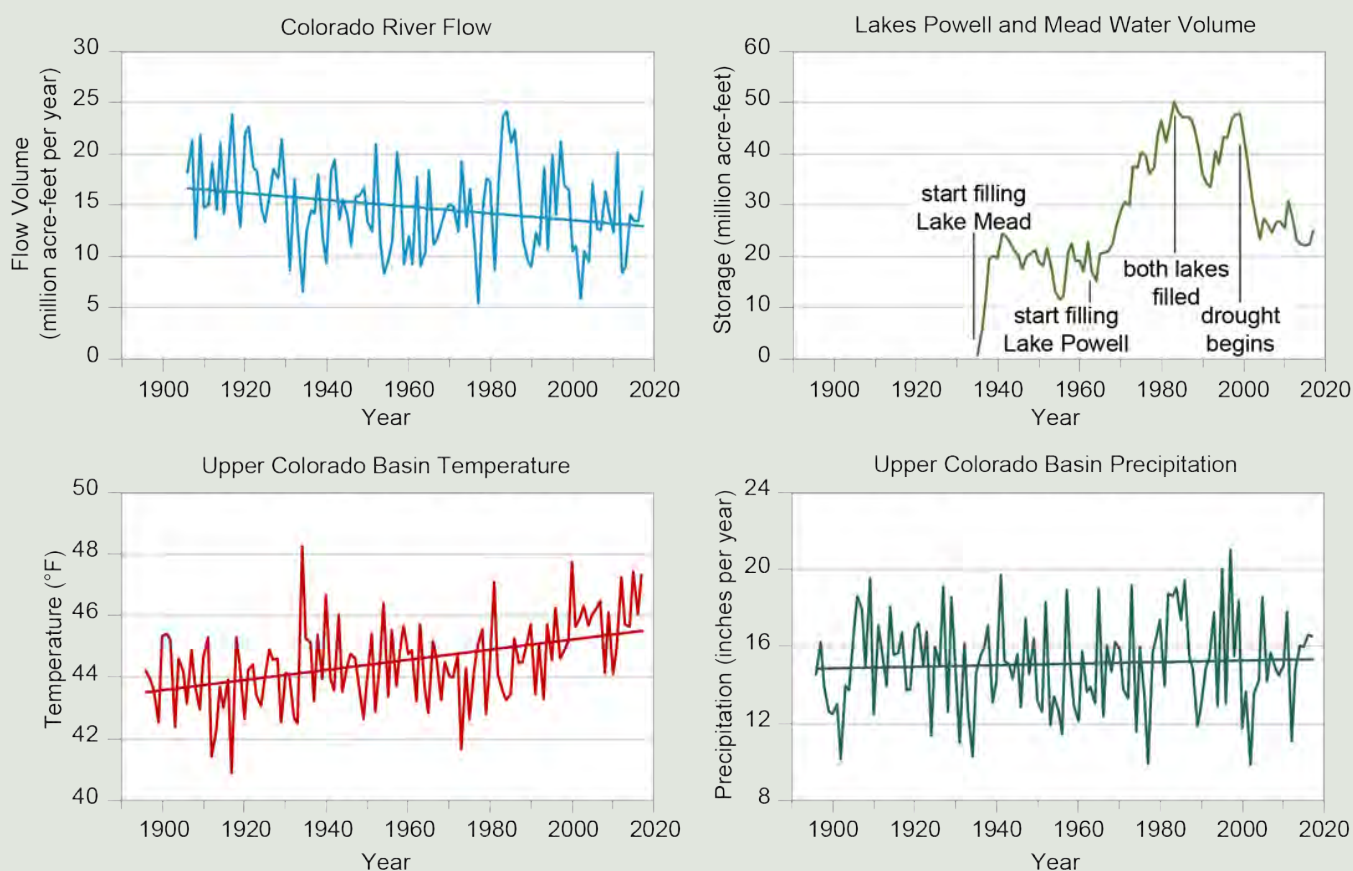


Figure 25.3: Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled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

Key Message 2

Ecosystems and Ecosystem Services

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

The forests and other ecosystems of the Southwest region that provide natural habitat and essential resources for people have declined in fundamental ways due in part to climate change. Vast numbers of trees have died across Southwest forests and woodlands,^{143,144,145,146} disproportionately affecting larger trees.¹⁴⁷ Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due in part to climate change.¹⁴⁶ Field measurements showed that changes attributable, in part, to climate

change, including increases in temperature, wildfire,⁷ and bark beetle infestations,^{148,149} outweighed non-climate factors such as fire exclusion or competition for light.¹⁴⁶

Wildfire is a natural part of many ecosystems in the Southwest, facilitating germination of new seedlings and killing pests. Although many ecosystems require fire, excessive wildfire can permanently alter ecosystem integrity.^{150,151} Climate change has led to an increase in the area burned by wildfire in the western United States.^{7,152} Analyses estimate that the area burned by wildfire from 1984 to 2015 was twice what would have burned had climate change not occurred (Figure 25.4).⁷ Furthermore, the area burned from 1916 to 2003 was more closely related to climate factors than to fire suppression, local fire management, or other non-climate factors.¹⁵²

Climate change has driven the wildfire increase,^{7,153} particularly by drying forests and making them more susceptible to burning.^{154,155} Specifically, increased temperatures have intensified drought in California,¹⁴ contributed to drought in the Colorado River Basin,^{12,13}

Climate Change Has Increased Wildfire

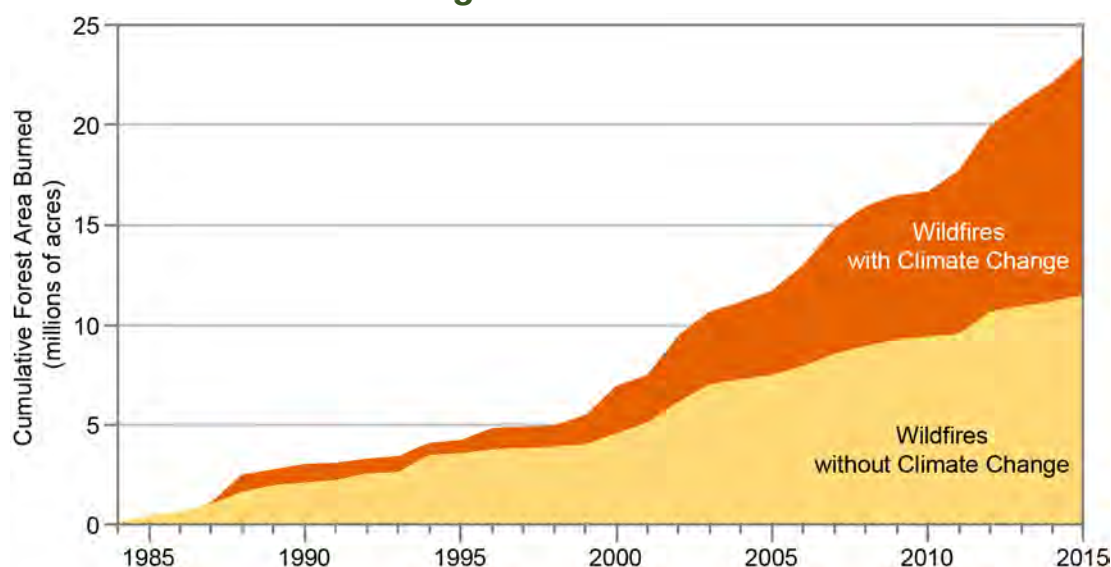


Figure 25.4: The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. Source: adapted from Abatzoglou and Williams 2016.⁷

reduced snowpack,^{46,49,156} and caused spring-like temperatures to occur earlier in the year.¹⁰¹ In addition, historical fire suppression policies have caused unnatural accumulations of understory trees and coarse woody debris in many lower-elevation forest types, fueling more intense and extensive wildfires.^{150,157}

Wildfire can threaten people and homes,¹⁵⁹ particularly as building expands in fire-prone areas. Wildfires around Los Angeles from 1990 to 2009 caused \$3.1 billion in damages (unadjusted for inflation).¹⁵⁹ Respiratory illnesses and life disruptions from the Station Fire north of Los Angeles in 2009 cost an estimated \$84 per person per day (in 2009 dollars).¹⁶⁰ In addition, wildfires degraded drinking water upstream of Albuquerque with sediment, acidity, and nitrates^{161,162} and in Fort Collins, Colorado, with sediment and precursors of cancer-causing trihalomethane, necessitating a multi-month switch to alternative municipal water supplies.^{163,164}

Ecosystems can naturally slow climate change by storing carbon, but recent wildfires have made California ecosystems and Southwest forests net carbon emitters (they are releasing more carbon to the atmosphere than they are storing).^{6,144,165} Wildfire has also exacerbated the spread of invasive plant species and damaged habitat. For example, repeated wildfire in sagebrush in Nevada and Utah has caused extensive invasions of cheatgrass, reducing habitat for the endangered sage-grouse.^{64,166}

Post-wildfire erosion damages ecosystems by denuding hillsides, such as occurred in Valles Caldera National Preserve in New Mexico when the 2011 Las Conchas Fire generated the biggest local erosion event in 1,000 years.¹⁶⁷ In New Mexico, consecutive large wildfires degraded habitat and reduced abundance of six out of seven native coldwater fishes and some native insects, although nonnative fishes were less affected.¹⁶⁸

With continued greenhouse gas emissions, models project more wildfire across the Southwest region.^{169,170,171,172,173} Under higher emissions (SRES A2)¹⁷⁴ (see the Scenario Products section of App. 3), fire frequency could increase 25%,¹⁷² and the frequency of very large fires (greater than 5,000 hectares) could triple.¹⁶⁹ The Santa Ana winds and other very dry seasonal winds increase fire risk in California¹⁷⁵ and Mexico.¹⁷⁶ Under higher emissions (SRES A2), sediment flows after fires would double in one-third of western U.S. watersheds modeled,¹⁷⁷ with the sediment potentially damaging ecosystems, homes, roads, and rail lines (Ch. 12: Transportation; Ch. 17: Complex Systems). Under the higher scenario (RCP8.5), cumulative firefighting costs for the Southwest could total \$13 billion from 2006 to 2099 (in 2015 dollars, discounted at 3%).¹⁷⁸

Reducing greenhouse gas emissions can reduce ecological vulnerabilities to wildfire.¹⁷⁹ For example, under a higher emissions scenario (SRES A2), climate change could triple burned area (in a 30-year period) in the Sierra Nevada by 2100, while under a lower emissions scenario (SRES B1¹⁷⁴), fire would only slightly increase.¹⁷³

Allowing naturally ignited fires to burn in wilderness and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change.^{180,181,182,183,184} These actions can naturally reduce or slow climate change because long-term storage of carbon in large trees can outweigh short-term emissions.^{185,186} Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires and protected their stores of carbon.^{187,188,190,191}

Climate change has also contributed to increased forest pest infestations, another

major cause of tree death in Southwest forests and woodlands (Ch. 17: Complex Systems, Box 17.4). Bark beetle infestations killed 7% of western U.S. forest area from 1979 to 2012,^{148,149} driven by winter warming due to climate change^{103,192} and by drought.¹⁹³ Tree death from bark beetles in Colorado increased organic matter in local streams, elevating precursors of cancer-causing trihalomethane in local water treatment plants¹⁹⁴ to levels that exceed the maximum contaminant levels for drinking water specified by the U.S. Environmental Protection Agency.¹⁹⁵ Without greenhouse gas emissions reductions, further increases in heat and drought could kill many more trees,^{143,196,197} especially affecting piñon pine,¹⁹⁸ whitebark pine,¹⁹⁹ and tall old-growth trees.²⁰⁰ Drought hastens tree mortality over a wide range of temperatures.²⁰¹ On the Colorado Plateau in Utah, five years of hotter temperatures in experiments killed microbial biocrusts, which conserve soil fertility and protect soils from erosion.^{202,203,204} In addition, grasslands^{205,206} and desert plants^{207,208} are vulnerable to increased plant death.

Field research in Southwest ecosystems has detected geographic shifts (Ch. 7: Ecosystems) of both plant and animal species, partly attributable to climate change. In Yosemite National Park, forest shifted into subalpine meadows from 1880 to 2002,²⁰⁹ and small mammals shifted 1,600 feet (500 m) upslope from 1914 to 2006,²¹⁰ with climate change outweighing other factors as the cause.^{209,210} Across the United States, including the Southwest, birds shifted northward between 0.1 and 0.5 miles (0.2 to 0.8 km) per year from 1975 to 2004, and analyses attribute the shift to climate change.^{211,212}

Continued climate change would cause north-south or upslope shifts of biomes (major vegetation types) in the Southwest as vegetation follows cooler temperatures.²¹³ Areas highly vulnerable to such biome shifts include the Arizona Sky

Islands²¹⁴ and the Sierra Nevada.²¹⁵ Potential shifts of suitable habitat for individual species include the shifting of Joshua tree habitat out of much of Joshua Tree National Park,^{207,216} American pika habitat shifting off of mountain tops,^{217,218} and upslope or northward shifts of numerous birds and reptiles across the Southwest.^{219,220,221} Climate change may also cause shifts in the timing of plant and animal life events (phenology), including flower blooming, plant leafing, and breeding time of birds and other animals.^{222,223,224} The arrival of migrating broad-tailed hummingbirds in Colorado advanced five days between 1975 and 2011.²²⁵ Plant species that provide essential food (nectar) for the hummingbirds also shifted in phenology (Ch. 7: Ecosystems), but much more than the birds, potentially jeopardizing breeding success.

To prepare for potential future ecological changes, U.S. federal agencies have begun to integrate climate change science into resource management planning in the Southwest. For example, the U.S. National Park Service has developed park plans with specific actions for managing resources under climate change.²²⁶ On private lands, planning that integrates native plants and wildlife into working landscapes such as farms, orchards, and ranches can promote conservation outside of protected areas and provide valued ecosystem services,



The 2013 Rim Fire in California burned more than 257,000 acres, the second largest wildfire in the Sierra Nevada and the third largest fire in California since 1932. Photo credit: Mike McMillan, U.S. Forest Service.

as demonstrated for rangelands by the Malpai Borderlands Group in Arizona and New Mexico.^{227,228} In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to provide funds to thin forest around the town perimeter.^{229,230} Ecosystem restoration provides an opportunity to integrate climate change considerations into natural resource management.²³¹ Desert research scientists have developed the ability to grow microbial biocrusts and are testing whether translocating biocrusts that are adapted to thrive at higher temperatures can restore the soil-stabilizing, nutrient-fixing, and other services that these organisms provide in many Southwest desert ecosystems.^{232,233,234} Finally, conservation of forests, especially coast redwoods, which have the highest carbon densities of any ecosystem in the world,²³⁵ can slow or reduce climate change by naturally removing carbon from the atmosphere.⁶

Key Message 3

The Coast

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

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016 (Figure 25.5),²³⁶ and in San Diego, sea level rose 9.5 inches (24 cm) from 1906 to 2016.²³⁷

Tidal gauges around the world show increases in sea level,^{238,239} and analyses show that climate change caused most of this rise by melting

of land ice and thermal expansion of ocean water.^{21,240,241} Non-climate-related land level changes influence relative sea level change. For example, between Cape Mendocino, California, and the Oregon border, lifting of the land at the San Andreas Fault has caused a drop in relative sea level between 1933 and 2016. Past earthquakes in the northern California coastal zone have abruptly lowered the shoreline and raised relative sea level.²⁴²

Under the higher scenario (RCP8.5), continued climate change could raise sea level near San Francisco by 30 inches (76 cm) by 2100, with a range of 19–41 inches (49–104 cm).²⁴² Currently, 200,000 people in California live in areas 3 feet (0.9 m) or less above sea level.⁹ Projections of sea level rise show that this population lives in areas at risk of inundation by 2100.⁹ Storm surges and high tides on top of sea level rise would exacerbate flooding.²⁴² In Redwood City, one-fifth of houses and one-quarter of roads are at risk of flooding under the higher scenario (RCP8.5) by 2100.²⁴³ Sea level rise and storm surge could completely erode two-thirds of southern California beaches by 2100²⁴⁴ and cause saltwater infiltration that would spoil groundwater at Stinson Beach in Marin County, California.²⁴⁵ Major seaports in Long Beach and Oakland and the international airports of San Francisco, Oakland, and San Diego are vulnerable. Projected sea level rise and storm surges could cause as much as \$5 billion (2015 dollars, undiscounted) in damage to property along the California coast from 2000 to 2100 under the higher scenario (RCP8.5).¹⁷⁸ In Point Reyes National Seashore, sea level rise threatens to inundate habitat for the endangered western snowy plover, harbor seals,²⁴⁶ and northern elephant seals,²⁴⁷ as well as archaeological Indigenous sites.

Governments and private landowners along the California coast have built seawalls, revetments, and other structures to protect against

sea level rise and storm surge, armoring 10% of the coastline.²⁴⁸ Because hard structures often alter natural water flows and increase coastal erosion, many parties are now exploring how to restore dunes, reefs, wetlands, and other natural features to protect the coast by breaking wave energy, to increase wildlife habitat, and to preserve public access to the coast.²⁴⁹

Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. The City of San Francisco²⁵⁰ is implementing a plan that limits building in low-lying areas, constructs terraced wetlands at India Basin to facilitate upland migration of marsh habitat, and protects San Francisco International Airport with berms and seawalls along the 8-mile (13 km) shoreline. Golden Gate National Recreation Area has produced a detailed spatial analysis of the vulnerability of the marsh, paths, and buildings at Crissy Field to sea level rise

and storm surges and has developed adaptation options, including moving infrastructure and establishing protective wetlands on inundated land.²⁵¹ In 2016, residents of the nine counties of the San Francisco Bay passed Measure AA, which provides funding for wetlands restoration to naturally reduce risks of flooding and inundation due to sea level rise and storm surge.

Ocean waters off the California coast and around the world warmed 0.6° to 0.8°F (0.3° to 0.5°C) from 1971 to 2010,²⁵² mainly due to human-caused climate change.²¹ Over the past century, sea surface temperatures in the northeast Pacific Ocean (including those off the coast of California) also experienced large year-to-year and decade-to-decade variations in response to changes in wind and weather patterns that altered the exchange of heat between the ocean and atmosphere and within the upper ocean,²⁵³ but showed overall warming from 1920 to 2016 (Figure. 25.6).

Sea Level Rise

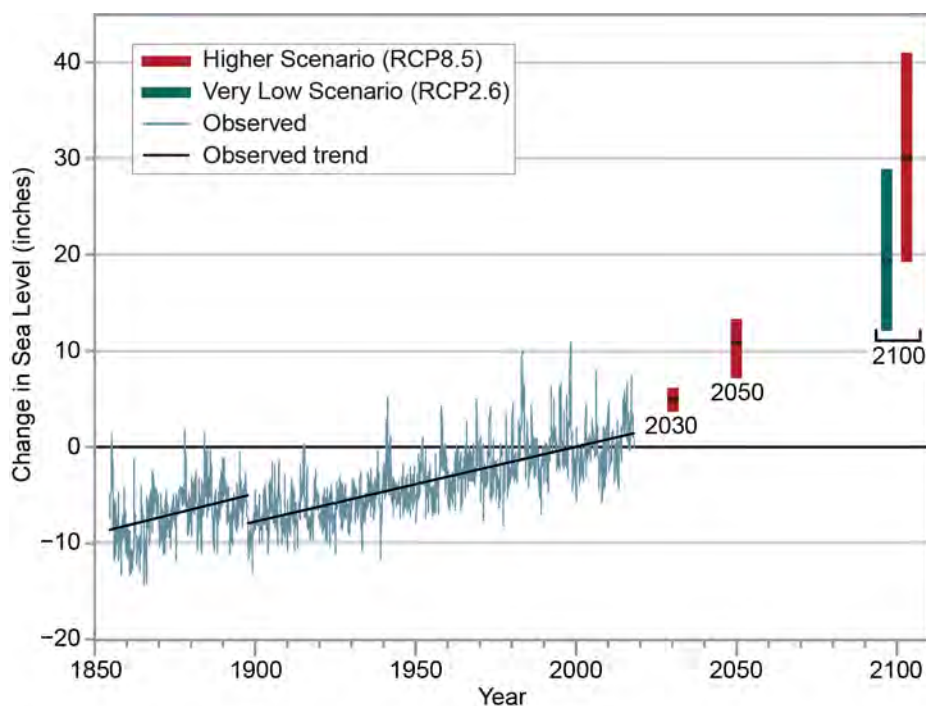


Figure 25.5: Sea level rise increases risks to infrastructure. At the Golden Gate Bridge in San Francisco, California, the tidal gauge with the longest time series in the Western Hemisphere shows that sea level has risen nearly 9 inches (22 cm) since 1854 (blue line).^{236,295} In 1897, the tidal gauge was moved, which caused a slight shift downward of the numerical level but no change in the long-term trend (trends indicated by the black lines). The bars show models projections of sea levels under a higher scenario (RCP8.5; red) and a very low scenario (RCP2.6; green).²⁴² The change in sea level is shown relative to the 1991–2009 average. Source: National Park Service.

Ocean Temperature Increase

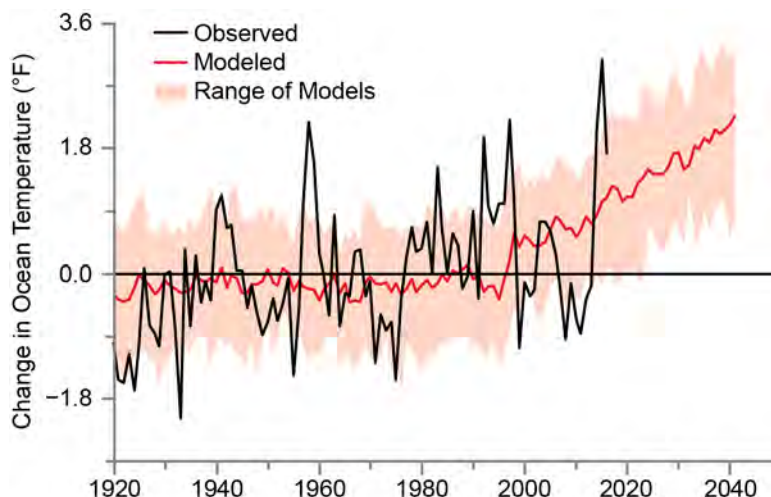


Figure 25.6 Ocean warming increases risks to fisheries and shellfish. The graph shows observed ocean temperatures of the California Current from measurements (black line); modeled temperatures, extended into the future under the higher scenario (RCP8.5; red line); and the range of 10% to 90% of the 28 models used (pink).^{254,296,297} Sources: National Park Service and NOAA.

The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change.²⁵⁴ The event led to the mass stranding of sick or starving birds and sea lions and shifts in pelagic (open water) red crabs and tuna into the region.²⁵⁵ The ecosystem disruptions contributed to closures of commercially important fisheries and substantial reductions in California salmon catches in 2016 and 2017.^{256,257,258} Ocean warming also contributed to an increase in harmful blooms of algae along the Pacific Coast.^{259,260,261,262} These harmful algal blooms have produced domoic acid, which can kill people who eat tainted shellfish^{261,263} and kill California sea lions.^{261,264,265} Harmful algal blooms and shellfish contamination in the record warm year of 2015 delayed the commercially important Dungeness crab fishery, which contributed to a substantially reduced catch. Shifts in the timing of Dungeness and rock crab fisheries into whale migration season in 2016 contributed to increases in whale entanglements in fishing gear.²⁶⁶

Continued climate change could warm California Current waters 4°–7°F (2°–4°C) above the 1980–2005 average by 2100 (Figure 25.6).²⁶⁷ This could contribute to more harmful algal blooms,^{259,261} deaths of birds and sea

lions, closures of fisheries, and economic loss to sectors dependent upon coastal marine resources. Under higher emissions (SRES A2), 28 fish species, including coho salmon and steelhead, could shift northward more than 180 miles (300 km) by 2050 due to higher sea surface temperatures.²⁶⁸ Marine heat waves may also increase in frequency, possibly causing local disappearance of some fish and economic losses.²⁶⁹

Observed ocean water acidity off the coast of California increased 25% to 40% (decreases of about 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to the early 2000s^{270,271} due to increasing emissions of carbon dioxide from human activities.^{21,272} Modeling studies show that human-caused changes in ocean acidity have increased beyond what would be expected from natural variations in the early-to-mid-20th century.²⁷³ Along the California coast, during some episodes of naturally acidic spring/summer upwelling of deeper ocean water, ocean acidity has quadrupled (a decrease of 0.7 pH units) to some of the most acidic values in the world.²⁷⁴ Increased ocean acidity along California's coast has dissolved shells of some small planktonic sea snails

(pteropods), exceeding their adaptive capacity, which was developed from evolution in natural acidic upwellings.^{275,276,277} In contrast, nearshore kelp forests in the northern Channel Islands off the California coast experienced few acidic events compared to local mainland sites in one three-year study.²⁷⁸

Higher carbon emissions (SRES A2) could increase the acidity of California coastal waters 40% (a decrease of 0.15 pH units) above 1995 levels by 2050.²⁷⁰ In addition to damaging marine ecosystems, ocean acidification increases risks of economic losses in the shellfish industry. One ecosystem modeling study suggests negative effects of projected ocean acidification on California's state-managed crab, shrimp, mussel, clam, and oyster fisheries, but an increase in the urchin fishery.²⁷⁹ Warming of ocean waters has reduced oxygen concentrations in the California Current System by 20% from 1980 to 2012.^{280,281} Dissolved oxygen variations in waters far offshore affect oxygen concentrations in the California Current System nearshore.^{280,282} This deoxygenation contributed to an expansion of Humboldt squid, a species that thrives in deoxygenated water, in the northeastern Pacific Ocean in the late 1990s.^{283,284} Invading Humboldt squid prey on hake and other fish that are commercially important to coastal fishing communities.²⁸³

Climate change may reduce ocean oxygen in Pacific Ocean waters to levels lower than any naturally occurring levels as early as 2030²⁸⁵ or 2050.²⁷³ Reduced oxygen could decrease rockfish habitat off southern California by 20% to 50%.²⁸⁶ Further deoxygenation may harm bottom-dwelling marine life, shrink open-water habitat for hake and other economically important species,²⁸⁷ and increase the number of invasions by squid. Tracking the variability of ocean waters and fish populations and adjusting catch quotas accordingly can reduce pressures on fisheries stressed by climate

change,²⁸⁸ actions that have been identified as parts of the National Oceanic and Atmospheric Administration's (NOAA) Fisheries Climate Science Strategy.²⁸⁹

With continued climate change, risks would cascade from one area to another. For example, projected warmer winter temperatures in the Sierra Nevada would increase winter runoff, reduce spring and summer freshwater inflows into San Francisco Bay, and increase salinity in the Bay 3 to 5 grams per kilogram of water by 2100.^{290,291,292} Also, sea level rise and storm surge would compound effects inland of river and stream flooding, putting houses and roads at risk of inundation and damage.^{293,294}

Key Message 4

Indigenous Peoples

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

Droughts in the Southwest have contributed to declines in traditional Indigenous staple foods, including acorns, corn, and pine nuts.^{298,299,300} Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands.³⁰¹ Navajo elders tell of the increasingly arid conditions over the last half of the 20th century that contributed to declines in culturally significant crops, the flow of specific water springs and seeps, and wildlife populations, such as eagles.^{44,302} Projected

reductions in water supply reliability,^{13,114} coupled with water agreements that involve selling or leasing tribal water to neighboring communities, could place tribal water supplies at risk during severe shortages. As water supplies decrease and water demand increases, tribes are at risk of finding themselves committed to providing purchased water to other entities, resulting in situations in which, in the words of one elder, “water sold must be delivered, regardless of the condition of the selling reservation. In this worst-case scenario, the Community will have to breach its contracts for the survival of its people.”³⁰³

In addition to drought, wildfires affect traditional resources, including fish, wildlife, and plants, such as tanoaks and beargrass, upon which some Southwest tribes rely for food and cultural uses.^{304,305,306} Continued climate change would reduce populations of some fish, wildlife, and plants that serve as traditional foods, medicines, and livelihood and cultural resources.^{298,307,308} Reduced availability of traditional foods often contributes to poorer nutrition and an increase in diabetes and heart disease.^{298,309} Reductions in runoff would, for example, increase the salinity of Pyramid Lake in Nevada, reducing fish biodiversity and affecting the cui-ui fish, the primary cultural resource of the Pyramid Lake Paiute Tribe.³¹⁰ Tribes in the Southwest that depend on livestock are at risk of climate-related degradation of rangelands.^{44,311,312} Many California tribes, including the Miwok, Paiute, Western Mono, and Yurok, among others, are concerned about the loss of acorns—a nutritious traditional food, medicine, and basketry component^{313,314}—due to sudden oak death, which can increase with changes in humidity and temperature.^{44,312,315} Changes in plant and animal ranges (Ch. 7: Ecosystems, KM 1) can also affect mental and spiritual health, disrupting cultural connections to disappearing plant and animal relatives and to place-based identity and practices.^{42,316}

Changes in marine ecosystems affect resources for Indigenous peoples (Ch. 15: Tribes). Ocean warming affects salmon and other fish on which Pacific Coast tribes rely for subsistence, livelihoods, and cultural identity.^{307,317,318,319,320} Ocean warming and acidification, as well as sea level rise, increase risks to shellfish beds (which reduces access for traditional harvesting),²⁹⁸ pathogens that cause shellfish poisoning,^{307,311} and damage to shellfish populations, which can cause cascading effects in food and ecological systems upon which some tribes depend.^{298,321}

Although Indigenous peoples have adapted to climate variations in the past, historical inter-generational trauma, extractive infrastructure, and socioeconomic and political pressures^{322,323} reduce their adaptive capacity to current and future climate change (Ch 15: Tribes, KM 1 and 3).³²⁴ Still, in response to climate change, Indigenous peoples in the Southwest are developing new adaptation and mitigation actions based on a cultural model focused on relationships between humans and nonhumans.^{313,325,326} Traditional ecological knowledge of specific plants and habitats can enable Indigenous peoples to provide early detection of invasive species and support to ecological restoration.³²⁷ Some tribes, such as the Tesuque Pueblo of New Mexico, use their knowledge to reintegrate traditional foods into their diets. Other tribes, such as the Karuk Tribe,³⁰⁴ North Fork Mono,³¹³ and Mountain Maidu³²⁸ use traditional ecological knowledge to guide natural resource management. The Yurok Tribe, Gila River Indian Community, and Tohono O’odham Nation, among others, are developing climate adaptation plans, often in partnership with universities and other research institutions (Ch. 15: Tribes, KM 3 and Figure 15.1).

Many Indigenous peoples in the Southwest region have traditionally used fire as a tool central to cultural and spiritual practices. They use fire to protect and enhance species used for basket weaving, medicines, and traditional

foods.^{306,313,328,329,330,331,332} This cultural use of fire offers an important tool for adaptation and mitigation, as traditional burning reduces fuel

accumulations that can lead to high-severity wildfires (see Case Study “Cultural Fire and Climate Resilience” and Figure 25.7).^{331,333}

Case Study: Cultural Fire and Climate Resilience

Indigenous peoples in the Southwest have traditionally used fire as a tool central to social, cultural, and spiritual practices. They use fire to increase ecosystem resilience, reduce fuel loads, manage crops, and protect species used for basket weaving, medicines, and traditional foods.^{306,313,328,329,330,331,332} Tribal entities are restoring cultural burning practices and management principles that guide the use of fire on the landscape to reduce wildfire risks and protect public and tribal trust resources.^{331,333} For example, Yurok tribal members have formed the Cultural Fire Management Council (CFMC), in partnership with the Nature Conservancy Fire Learning Network, Firestorm Inc., Yurok Forestry/Wildland Fire, Northern California Indian Development Council, and the U.S. Department of Agriculture (USDA) Forest Service, to bring fire back to the landscape for ecosystem restoration.³³⁴ The collaboration builds capacity and trains Yurok and local fire crews through the Prescribed Fire Training Exchange. “Restoration of the land means restoration of the people,” said CFMC President Margo Robbins, “Returning fire to the land enables us to continue the traditions of our ancestors.”³³⁴



Cultural Fire on Yurok Reservation

Figure 25.7: Andy Lamebear, a Yurok Wildland Fire Department firefighter and Yurok tribal member, ignites a cultural burn on the Yurok Reservation. The tribe uses low- to medium- intensity fires to enhance the production of plant-based medicines, traditional basket materials, native fruits, and forage for wildlife. Cultural burning also reduces risks of catastrophic wildfire. Photo courtesy of the Yurok Tribe.

Key Message 5

Energy

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

Hydroelectric generation depends on sufficient water supplies. The severe drought in California, intensified by climate change,^{14,56} reduced hydroelectric generation by two-thirds from 2011 to 2015.³³⁵ Drought in the Colorado River Basin^{13,59} caused river runoff, on which hydroelectric generation depends,^{12,336,337} to decline. By 2016, Lake Mead, which stores water for drinking, agriculture, and the Hoover Dam hydroelectric plant, had fallen by half (Box 25.1 and Figure 25.3). Although the Bureau of Reclamation maintained constant electricity generation at Hoover Dam throughout the drought, this decline potentially reduces maximum generation capacity.

In California, utilities increased fossil fuel generation of electricity to compensate for the drought-driven decline in hydroelectricity, increasing state carbon dioxide emissions in the first year of the drought (2011 to 2012) by 1.8 million tons of carbon, the equivalent of emissions from roughly 1 million cars.^{338,339} A drop in the price of natural gas also contributed to the increase, although the shift from hydroelectric to fossil fuels cost California an estimated \$2.0 billion (in 2015 dollars).³⁴⁰ Other southwestern states also shifted some generation from hydropower to fossil fuels.⁸⁹

Under a higher scenario (RCP8.5), declines in snowpack and runoff in the Colorado River and Rio Grande Basins and a shift of spring runoff to earlier in the year¹⁰⁵ would reduce hydroelectric power potential in the region by up to 15% by 2050.⁹¹ Under a very low scenario (RCP2.6), hydroelectric generation may remain unchanged, demonstrating the positive benefits of emissions reductions.⁹¹ With increased precipitation, hydroelectric potential could increase,³⁴² except in cases of reservoir spillage to protect dams in extreme storms.³⁴³

The efficiency of water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest region by 2050.⁹¹ Since higher temperatures also increase electric resistance in transmission lines, electricity losses in many transmission lines across the Southwest could reach 5% by 2080 under a lower scenario (RCP4.5) and 7% under a higher scenario (RCP8.5).³⁴⁴ Under the higher scenario (RCP8.5), water demand by thermoelectric plants in the Southwest is projected to increase 8% by 2100.³⁴⁵ In a 10-year drought, summer electric generating potential in the Southwest could fall 3% to 9% under higher emissions (SRES A2) or 1% to 7% under lower emissions (SRES B1; Figure 25.8).³⁴⁶

Any increase in water requirements for energy generation from fossil fuels would coincide with reduced water supply reliability from projected decreases in snowpack^{46,77} and earlier snowmelt.^{75,347} Increased agricultural water demands under higher temperatures could affect the seasonal demand for hydropower electricity.¹⁰⁵ The water consumption, pollution, and greenhouse gas emissions of hydraulic fracturing (fracking) make that source of fuel even less adaptive under climate change.³⁴⁸ Substantial energy and carbon emissions are embedded in the pumping, treatment, and

transport of water, so renewable-powered water systems are less energy and carbon intense than ones powered by fossil fuels.³⁴⁹

Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest. For example, wind energy generation in California rose by half from 2011 to 2015, and solar energy generation increased by 15 times.³³⁵

Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. By cutting carbon emissions, renewable energy can reduce future impacts of climate change on nature and human well-being.^{30,350,351,352} After the first year of the drought, when natural gas burning increased to compensate for a loss of hydroelectric energy, solar and wind energy sources in California increased enough to displace 15% of fossil fuel burning for electricity from 2012 to 2017, thereby reducing state greenhouse gas emissions by 6%.³³⁵ Increased electricity generation by renewable sources

can cut water needs up to 90% in the Southwest, depending on the fraction of production derived from fossil fuels.^{353,354} Under a higher scenario (RCP8.5), conversion of two-thirds of fossil fuel plants to renewables would reduce water demand by half.³⁴⁵

State energy policies are facilitating the switch to renewable energy. Arizona, California, Colorado, Nevada, and New Mexico have enacted renewable energy portfolio standards.⁹³ California has set the highest standard: 50% of energy generation from renewable sources by 2030. In 2017, renewable energy sources supplied 32% of California energy generation.³⁵⁵ By 2013, these standards had averted 26 trillion watt-hours of fossil fuel generation in the Southwest and 3% of carbon emissions nationally and had produced \$5 billion in health benefits from reduced air pollution (in 2013 dollars; \$5.2 billion in 2015 dollars).³⁵⁶ Potential future benefits of existing renewable portfolio standards include carbon emission reductions of 6% nationally and health benefits of \$560 billion (in 2013 dollars; \$577 billion in 2015 dollars) from 2015 to 2050.³⁵⁷

Electricity Generation Capacity at Risk Under Continued Climate Change



Figure 25.8: Under a higher emissions scenario (SRES A2¹⁷⁴), heat-induced reduction of energy efficiency and reduced water flows would reduce summer energy generation capacity across the Southwest region. These projected reductions would increase risks of electricity shortages. The map shows projected changes for the period 2040–2060 compared to the period 1949–2010. Source: adapted from Bartos and Chester 2015.³⁴⁶ Reprinted by permission from Macmillan Publishers Ltd. This figure was revised in June 2019. See Errata for details: <https://nca2018.globalchange.gov/downloads>

Distributed solar energy systems place individual solar panels on roofs, on parking lot canopies, and other built places. The high number of sunny days in the Southwest and the great extent of existing rooftops and parking lots create a high potential for distributed solar generation, which could provide two-thirds of electricity use in California.³⁵⁸ Distributed solar uses land that has already been urbanized and is close to energy users, reducing the need for transmission lines and transmission line electricity losses. Compared to industrial centralized solar power systems, distributed solar causes less death and disruption to wildlife that are already vulnerable to climate change, such as birds and endangered desert tortoises.³⁵⁹ California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, in particular net metering, in which customers sell their excess solar electricity to the grid.³⁶⁰ Distributed wind energy systems can provide similar benefits.

Arizona, California, Colorado, Nevada, and New Mexico have enacted energy efficiency standards for utilities. California and New Mexico have also enacted policies that decouple utility profits from electricity sales.³⁶¹ White or reflective roofs, known as cool roofs, increase energy efficiency of buildings. Under a higher scenario (RCP8.5), cool roofs would reduce urban heat islands in Los Angeles and San Diego 2°–4°F (1°–2°C) by 2050 and decrease energy use and the use of air conditioning.³⁶² Urban tree planting in Phoenix that would increase tree cover from 10% to 25% would provide daytime cooling of up to 2°C in local neighborhoods.³⁶³

Newer technologies now allow generating plants to use nontraditional water sources, including saline groundwater, recycled water from landscaping, and municipal and industrial wastewater. For example, the Palo Verde Nuclear Generating Station in Arizona

uses municipal wastewater.³⁶¹ Other plants in the region use extremely water-efficient hybrid wet-dry cooling technology. For instance, the Afton Generating Station in New Mexico is a natural gas combined-cycle plant that uses hybrid cooling to reduce water intensity by 60% compared to conventionally cooled plants.³⁶¹

Electric cars can reduce fossil fuel use and greenhouse gas emissions compared to gasoline-powered vehicles. The relative greenhouse gas emissions from electric and gasoline vehicles depend on how the electricity is generated.^{364,365} If the electricity is produced from renewable sources, then the operating emissions for electric vehicles are near zero, although the manufacturing of the vehicle emitted greenhouse gases. Conversely, if the electricity is produced completely from fossil fuel, the emissions from the electric vehicle are higher because of the limit of energy efficiency of large power plants and transmission line losses. Because sunlight, wind, and other renewable resources are intermittent and sometimes not available at times of demand, charging at night and improvements in battery technology would facilitate renewable energy generation.

Key Message 6

Food

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

Climate change has altered factors fundamental to food production and rural livelihoods in the Southwest, particularly the shortage of water caused by droughts in California^{14,56} and the Colorado River Basin.¹³ The California drought led to losses of more than 10,000 jobs and the fallowing of 540,000 acres (220,000 hectares), at a cost of \$900 million in gross crop revenue in 2015.¹³⁰ Increased temperatures in the Southwest also affected agricultural productivity from 1981 to 2010.³⁶⁶

Food production depends on reliable surface and groundwater supplies, which decline from droughts and reductions in snowpack and soil moisture.⁶⁷ Irrigated agriculture and livestock water use accounted for approximately three-quarters of total water use in the Southwest in 2010, excluding Colorado, which has wide-ranging dryland wheat production.^{16,367,368} In the recent California drought, domestic wells dried out in some rural communities, but increased groundwater pumping from deeper wells prevented some agricultural revenue losses.³⁶⁹ Falling groundwater tables increase pumping costs and require drilling to deepen wells.¹³⁰ Drought-related agricultural changes, stricter drilling regulations, and rapid aquifer depletion have already led to a decline in irrigation in parts of the region. According to climate projections for lower and higher emissions scenarios (RCP4.5 and RCP8.5), future changes in climate would reduce aquifer recharge in the southern part of the region by 10%–20%,³⁷⁰ removing some of the secondary water source responsible for buffering effects of severe drought. In the Gila River Basin of New Mexico, farmers shift to groundwater pumping when surface water supplies are reduced, despite associated increases in production costs.³⁷¹ Under continued climate change, increased drought risk¹³ and higher aridity⁷⁰ could expose some agricultural operations in the Southwest to less reliable surface and groundwater supplies (Ch. 10: Ag & Rural, KM 1).

Under continued climate change, higher temperatures would shift plant hardiness zones northward and upslope (Figure 25.9). These changes would affect individual crops differently depending on optimal crop temperature thresholds. Some crops, including corn³⁷² and rice,³⁷³ are already near optimal thresholds in the Southwest. Increasing heat stress during specific phases of the plant life cycle can increase crop failures, with elevated temperatures associated with failure of warm-season vegetable crops and reduced yields or quality in other crops.³⁷⁴ While crops grown in some areas might not be viable under hotter conditions, crops such as olives, cotton, kiwi, and oranges may replace them.³⁷⁵ In parts of the Southwest region, increasing temperatures would prompt geographic shifts in crop production, potentially displacing existing growers and affecting rural communities.³⁷⁶ Wine grape quality can be particularly influenced by elevated temperatures.³⁷⁷ Increased levels of ozone and carbon dioxide near the surface, combined with increases in temperature, can decrease food quality and nutritive values of fruit and vegetable crops.^{378,379}

Because many fruit and nut trees require a certain period of cold temperatures in the winter, decreased winter chill hours under continued climate change would reduce crop yields, though the magnitude may vary considerably.³⁸⁰ In Yolo County, California, reduced winter chill may make conditions too hot for walnut cultivation by 2100.³⁸¹ California almond acreage has nearly doubled over the last two decades due to high foreign demand and the favorable Mediterranean climate. California now produces over 80% of world almond supply.³⁸² Since almonds also have a relatively high water requirement, both water and adequate cool winter temperatures will be important factors to maintain California tree nut production under climate change.

Projected Shift in Agricultural Zones

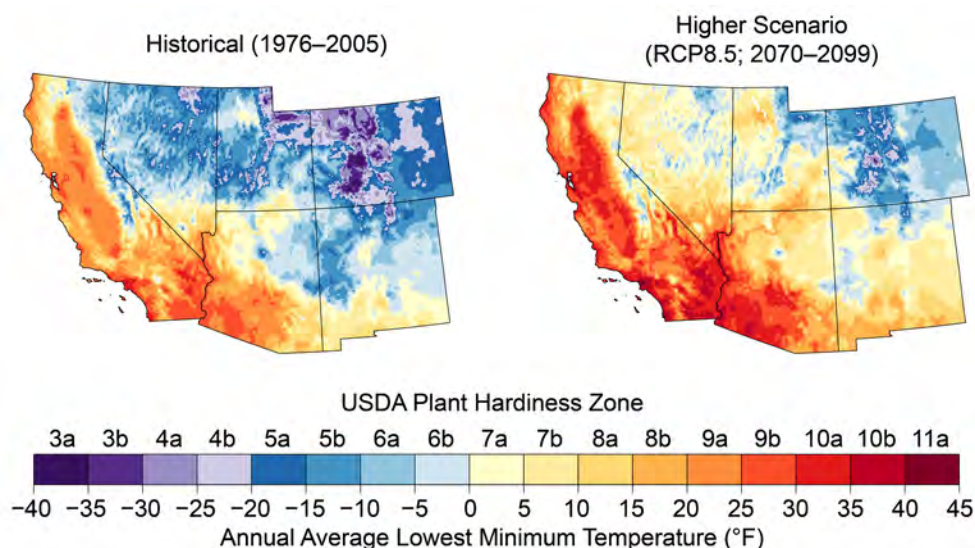


Figure 25.9: The U.S. Department of Agriculture plant hardiness zones indicate the cold temperature requirements of crops. Increases in temperature under the higher scenario (RCP8.5), would shift these zones northward and upslope, from the period 1976–2005 (left, modeled historical) compared to projections for 2070–2099 (right, average of 32 general circulation models). Sources: NOAA NCEI and CICS-NC.

Climate-related vulnerabilities of the Southwest region's livestock industry include reduced long-term livestock grazing capacity, reduced feed supply, increased heat stress (Ch. 10: Ag & Rural, KM 3), and reduced forage quality.³⁸³ Water-intensive forage crops are especially vulnerable to water shortages.¹⁵ Although livestock production systems persist in highly variable conditions, projected high temperatures may decrease production of rangeland vegetation and livestock forage.³⁸⁴ In response to drought (1999–2004), 75% of Utah ranch operations reported major reductions in water supply, forage, and cattle productivity.³⁸⁵ Only 14% felt they were adequately prepared for the drought, which may be reflected in the high use of federal relief programs.

One potential adaptation of agriculture to drought is water banking, the storage of excess surface water in groundwater aquifers.^{386,387} For example, streamflows from the Sierra Nevada in high-precipitation years could provide substantial groundwater recharge in the California Central Valley.³⁸⁸ Additional options include expanding surface reservoir storage or relying

upon groundwater pumping, although this further depletes limited groundwater stores.³⁸⁹

Flexible livestock management strategies, such as stocking rates, grazing management practices, employing livestock bred for arid environments, erosion control, and identification of alternate forage supplies can help reduce vulnerability in an increasingly arid and variable climate.^{390,391} Criollo cattle appear well-suited for the arid Southwest because they are more heat tolerant and adaptive than traditional breeds.³⁹²

In urban areas across the Southwest, such as Tucson, Arizona, and Sacramento, California, community food banks that grow food in community gardens can help maintain food security in a drier and more variable climate. Urban gardens and local food organizations provide fresh produce, foster community education, and support networks of local growers. These organizations build food systems capacity, which helps to mitigate impacts of urban heat, reduces food transportation costs and

emissions, and supports provision of fresh local food to low-income urban dwellers.

Additional emerging issues that increase risks to food production include invasive nonnative or alien insect pests (introduced into the region intentionally or unintentionally) that are more adapted to hotter temperatures.³⁹³ Global trade and efficient transportation also increase risks of invasion by alien insect pests. A mismatch in timing between plant flowering and the arrival of insect pollinators would reduce crop production and pollinator survival.³⁹³ In addition, some subsistence foods, such as fish, upon which some Indigenous and other subsistence and urban communities depend,^{309,394,395,396,397} and spiritually, socially, and culturally important tribal traditional foods²⁹⁸ would be vulnerable in a drier and more variable climate (Key Message 4).

Key Message 7

Human Health

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

Exposure to hotter temperatures and heat waves has led to heat-associated deaths and illnesses in Arizona and California.^{398,399,400,401,402,403} In the unprecedented 2006 California heat wave, which affected much of the state and part of Nevada, extremely high temperatures occurred day and night for more than two weeks.⁴⁰⁴ Compared to non-heat wave summer days, it is estimated that the event led to an additional 600 deaths, 16,000

emergency room visits, 1,100 hospitalizations in California,^{399,405,406} and economic costs of \$5.4 billion (in 2008 dollars).⁴⁰⁵ Parts of the Southwest region experienced record-breaking heat in five of the six years from 2012 to 2017.^{25,26,27,28,29} Assessments of the health impacts associated with record high temperatures in parts of the Southwest since 2010 are not yet available in the scientific literature.

Under continued climate change, projected increases in hot days and extreme heat events in the Southwest (Figure 25.10)^{23,24,404,407} will increase the risk of heat-associated deaths.³⁰ Under the higher scenario (RCP8.5), the Southwest would experience the highest increase in annual premature deaths due to extreme heat in the country, with an estimated 850 additional deaths per year and an economic loss of \$11 billion (in 2015 dollars) by 2050.¹⁷⁸ Under a lower scenario (RCP4.5), deaths and costs would be reduced by half compared to the higher scenario (RCP8.5).¹⁷⁸ By 2090, deaths and economic losses would more than double from 2050 under all emissions scenarios.¹⁷⁸ Heat and other environmental exposures particularly affect outdoor workers.¹⁷⁸ Under the higher scenario (RCP8.5), extreme heat in the Southwest (Figure 25.10) would also lead to high labor losses, including losses of high-risk labor hours of up to 6.5% for some counties by 2090 and of \$23 billion per year in regionwide wages (in 2015 dollars).¹⁷⁸ It is projected that the lower scenario (RCP4.5) would reduce those wage losses by half.¹⁷⁸

The risk of illness or death associated with extreme temperatures can be reduced through targeted public health and clinical interventions.^{30,32} The main factors that put individuals and populations at increased risk in a heat wave are age (children and older adults are most at risk), hydration status, and presence of a chronic disease such as obesity, cardiovascular or respiratory disease, or psychiatric illness.^{400,408,409,410,411,412,413,414,415} Psychosocial stresses and socioeconomic conditions, such as hot and poorly ventilated homes or lack of access to public emergency cooling centers can elevate these risks.^{31,33,416}

Without adoption and implementation of strategies to minimize exposures to extended periods of extreme heat, the public health impacts of future heat waves may be as serious as those observed in California in 2006. The technological and behavioral adaptations to heat developed by populations in the Southwest are based on the observed historical range of nighttime minimum temperatures.⁴⁰⁴ Projected increases in minimum temperatures and decreases in the number of cool nights²³ may diminish the efficacy of these adaptations.

Climate change and variability can also increase communicable and chronic disease burdens.^{417,418,419} While infectious diseases like plague and hantavirus pulmonary syndrome disproportionately affect the Southwest region,¹⁵⁸ new research to support estimating future climate-associated risk for these diseases is sparse.⁴²⁰ Therefore, this assessment focuses on recent developments in the understanding of heat, air quality, mosquito-borne diseases, and Valley fever and vulnerabilities that influence them.

In addition to extreme heat, the environmental conditions of greatest concern for human health are ground-level ozone air pollution, dust storms, particulate air pollution (such as from wildfires and dust storms), aeroallergens (airborne substances that trigger allergic reactions), and low water quality and availability.^{30,178} In addition, alternating episodes of drought and extreme precipitation coupled with increasing temperatures promote the growth and transmission of pathogens.^{30,421} The risk of onset or exacerbation of respiratory and cardiovascular disease is associated with a single or a combined exposure to ground-level ozone pollution, particulate air pollution, respiratory allergens, and extreme heat. Ground-level ozone is produced by chemical reactions of combustion-related chemicals (for example, from vehicles or wildfires) in a reaction that is dependent on ultraviolet radiation (that is, from the sun) and amplified by higher temperatures. Once formed, ozone can travel great distances and persist in high concentrations overnight in rural areas. Among many health impacts, ozone can promote or aggravate asthma and respiratory allergies.^{422,423,424,425}

Projected Increases in Extreme Heat

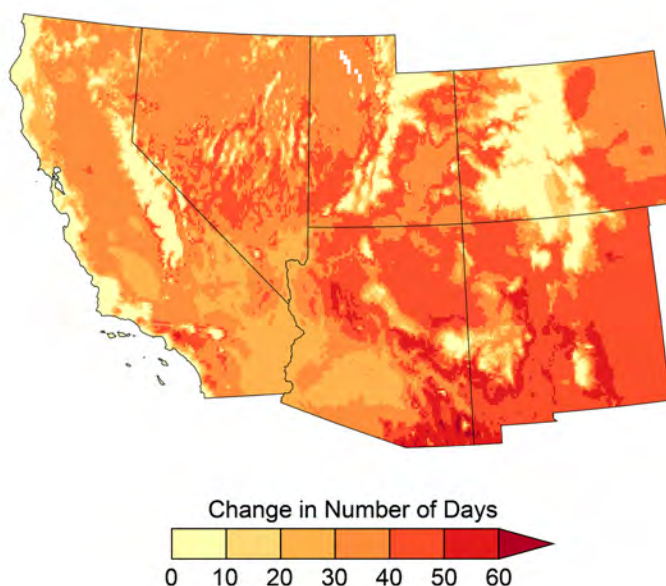


Figure 25.10: Under the higher scenario (RCP8.5), extreme heat would increase across the Southwest, shown here as the increase in the average number of days per year when the temperature exceeds 90°F (32°C) by the period 2036–2065, compared to the period 1976–2005.²³ Heat waves increase the exposure of people to heat stroke and other illnesses that could cause death.³⁰ Source: adapted from Vose et al. 2017.²³

Elevated levels of CO₂ in conjunction with higher temperatures can increase the amount and potency of aeroallergens (Ch. 14: Human Health, KM 1). These conditions may also lead to new cases or exacerbation of allergy and asthma.^{426,427,428,429} Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution, with the greatest mortality due to cardiovascular causes.⁴³⁰

Severe dust storms in the Southwest contribute to respiratory and cardiovascular disease.^{431,432} The association between Valley fever, a soilborne fungal respiratory infection of the Southwest, and warmer temperatures and soil dryness varies across the region and by time of year.^{189,433,434} The connection between climate change, dust storm frequency and severity, and future public health effects in the region is complex and remains an emerging area of research.^{435,436,437,438,439} Heat extremes, warming, and changes in precipitation will also influence the distribution and occurrence of vector-borne diseases like West Nile virus^{440,441,442,443} and may lead to the emergence of new disease (Ch. 14: Human Health, KM 1).³⁰ Without proactive interventions and policies that address the biological, exposure, and socioeconomic factors that influence individual and population vulnerability, adverse health impacts may increase (Ch. 14: Human Health, KM 2). Those increases may disproportionately affect people with the lowest incomes, which hinders adaptive capacity (Ch. 14: Human Health, KM 1).^{416,444}

Climate-related hazards such as heat waves, flooding, wildfires, or large disease outbreaks require emergency responses. Prolonged droughts can affect drinking water availability, reduce water quality,⁴⁴⁵ and send more people seeking medical treatment.^{446,447} The increased burden of disease can outpace the resources and adaptive capacity of public health and

clinical infrastructures. The region may not be prepared to absorb the additional patient load that could accompany climate change,⁴⁴⁸ but integrating risk reduction strategies into emergency response plans and recognizing and addressing vulnerability factors can appreciably reduce risks of future adverse health consequences (Ch. 14: Human Health, KM 3). This approach is embodied in the Centers for Disease Control and Prevention's (CDC) Building Resilience Against Climate Effects framework for adaptation planning.⁴⁴⁹ Adaptation planning is already yielding health protection benefits.⁴⁵⁰

Local government agencies are preparing for extreme events by developing and updating emergency response plans and improving public warning and response systems. In 2014, California updated its Contingency Plan for Excessive Heat Emergencies,⁴⁵¹ Arizona released its Heat Emergency Response Plan,⁴⁵² and Salt Lake City, San Francisco, and Sonoma County were recognized in the first cohort of U.S. Department of Energy Climate Action Champions. Integrated and participatory planning for extreme heat,⁴⁵³ such as the Capital Region Climate Readiness Collaborative in Sacramento, California, can help overcome institutional and governance barriers to implementing adaptation actions (Ch. 28: Adaptation).⁴⁵⁴

Policies and interventions related to one health factor can positively affect other factors and yield co-benefits.^{455,456,457,458,459} For example, research shows that heat-associated deaths and illnesses are preventable⁴⁶⁰ and that healthier individuals are less susceptible to adverse effects of extreme heat exposure. Obesity, which affects about 30% of adults and 15% of school-age children and teens nationwide, increases the risk for many chronic diseases, such as asthma and diabetes, and increases the risk for serious heat-related adverse health outcomes.^{32,461,462,463} Access to healthcare, social

isolation, housing quality, and neighborhood poverty are also key risk factors for heat-related health impacts.^{31,33,412}

Urban design strategies to address these risk factors include increasing walkability and bicycle safety and maintaining and planting trees and green space.⁴⁶⁴ These strategies can achieve multiple health benefits, including increasing physical activity, thereby helping residents maintain a healthy weight,^{465,466} reducing the urban heat island effect,⁴⁶⁷ and reducing exposure to harmful air pollutants from vehicles. Reducing the urban heat island effect also reduces energy demand and risks of power outages, which can contribute to health risks, such as patients losing access to electricity-dependent medical devices.

Climate change may weigh heavily on mental health in the general population and those already struggling with mental health disorders.^{468,469,470,471,472} One impact of rising temperatures, especially in combination with environmental and socioeconomic stresses, is violence towards others and towards self.^{473,474,475} Slow-moving disasters, such as drought, may affect mental health over many years.⁴⁷⁰ Studies of chronic stress indicate a potentially diminished ability to cope with subsequent exposures to stress.^{476,477,478}

Populations under chronic social and economic stresses in urban and rural areas possess lower psychological, physical, and economic

resilience (Ch. 10: Ag & Rural, KM 3). Communities that rely especially on well-functioning natural and agricultural systems in specific locations may be especially vulnerable to mental health effects when those systems fail. In the Southwest, the loss of stability and certainty in natural systems may affect physical, mental, and spiritual health of Indigenous peoples with close ties to the land.^{42,316} For example, extended drought raises concerns about maintaining Navajo Nation water-based ceremonies essential for spiritual health, livelihoods, cultural values, and overall well-being.³⁰¹

Acknowledgments

Technical Contributors

Mary E. Black

University of Arizona

Shallin Busch

National Oceanic and Atmospheric Administration

Brandon Goshi

Metropolitan Water District of Southern California

USGCRP Coordinators

Fredric Lipschultz

Senior Scientist and Regional Coordinator

Christopher W. Avery

Senior Manager

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Adaptation: cropped top and bottom to conform to the size needed for publication.

Traceable Accounts

Process Description

The authors examined the scientific literature in their areas of expertise. The team placed the highest weight on scientific articles published in refereed peer-reviewed journals. Other sources included published books, government technical reports, and, for data, government websites. The U.S. Global Change Research Program issued a public call for technical input and provided the authors with the submissions. The University of Arizona Center for Climate Adaptation Science and Solutions organized the Southwest Regional Stakeholder Engagement Workshop on January 28, 2017, with over 70 participants at the main location in Tucson, AZ, and dozens of participants in Albuquerque, NM, Boulder, CO, Davis, CA, Los Angeles, CA, Reno, NV, and Salt Lake City, UT, all connected by video. Participants included scientists and managers. The author team met the following day for their only meeting in person. Subsequently, authors held discussions in regular teleconferences. Many chapter authors met at the all-author meeting March 26–28, 2018, in Bethesda, MD.

Key Message 1

Water Resources

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

Description of evidence base

Research has found that hotter temperatures can make hydrologic droughts more severe. The unprecedented droughts in the Colorado River Basin and California showed that increased temperatures from climate change intensified the severity of the drought.^{13,14,56,59} Climate change, more than natural cycles, has reduced snowpack.^{46,49} Models project more drought under climate change,^{13,56,62} snowpack and streamflow decline in parts of the Southwest, and decreasing surface water supply reliability for cities, agriculture, and ecosystems.⁴⁷⁹

Major uncertainties

Projecting future streamflow and hydrologic characteristics in a basin contains many uncertainties. These differences arise because of uncertainty in temperature and precipitation projections due to differences among global climate models (GCMs), uncertainty in regional downscaling, uncertainty in hydrological modeling, and differences in emissions, aerosols, and other forcing factors. Another important uncertainty is differences in the hemispheric and regional-scale atmospheric circulation patterns produced by different GCMs, which generate different levels of snow loss in different model simulations. A key uncertainty is the wide range in projections of future precipitation across the Southwest;¹⁰⁵ some projections of higher-than-average precipitation in

the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.¹⁰⁵

Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Attribution of extreme events, such as the recent California drought to climate change, is an area of emerging science. On the one hand, Seager et al. (2015)⁵⁸ concluded that the California drought was primarily driven by natural precipitation variability. Sea surface temperature anomalies helped set up the high-pressure ridge over California that blocked moisture from moving inland. On the other hand, Diffenbaugh et al. (2015),⁵⁶ Williams et al. (2015),¹⁴ and Berg and Hall (2017)⁵⁵ concluded that high temperatures from climate change drove record-setting surface soil moisture deficits that made the drought more severe than it would have been without climate change. Storage of increased precipitation in soils may partially offset increased evaporation, possibly making drought less likely.⁴⁸⁰

In addition to the uncertainties in regional climate and hydrology projections and attribution studies, other uncertainties include potential changes in water management strategies and responses to accommodate the new changing baseline. Additionally, external uncertainties can impact water use in the region via legal, economic, and institutional options for augmenting existing supplies, adding underground storage and recovery infrastructure, and fostering further water conservation, changes in unresolved water rights, and changes to local, state, tribal, regional and national policies related to the balance of agricultural, ecosystem, and urban water use.

Description of confidence and likelihood

The *very high confidence* in historical droughts derives from the detection and attribution analyses of temperature increases, snow decreases, and soil moisture decreases that have documented hydrologic droughts in California and the Colorado River Basin due to anthropogenic climate change and the conclusions of the *Climate Science Special Report (CSSR)*, Volume I of the Fourth National Climate Assessment.⁷⁴ The *very high confidence* in drought projections derives from the multitude of analyses projecting drought in the Southwest under a range of emissions scenarios and the conclusions of the CSSR.⁷⁴ Only *medium confidence* is found for flood projections due to lack of consensus in the model projections of precipitation. Increasingly arid conditions and the potential for increased water use by people lead to an assessment of *high confidence* in the need for new ways to address increasing risks of water scarcity. The actual frequency and duration of water supply disruptions will depend on the preparation of water resource managers with drought and flood plans, the flexibility of water resource managers to implement or change those plans in response to altered circumstances,⁴⁸¹ the availability of funding to make infrastructure more resilient, and the magnitude and frequency of climate extremes.

Key Message 2

Ecosystems and Ecosystem Services

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

Description of evidence base

Scientific research in the Southwest has provided many cases of detection and attribution of historical climate change impacts. Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Published field research has detected ecological changes in the Southwest and attributed much of the causes of the changes to climate change. Wildfire across the western United States doubled from 1984 to 2015, compared to what would have burned without climate change, based on analyses of eight fuel aridity metrics calculated from observed data, historical observed temperature, and historical modeled temperature from global climate models.⁷ The increased heat has intensified droughts in the Southwest,^{13,14} reduced snowpack,^{49,156} and advanced spring warmth.¹⁰¹ These changes have dried forests,^{154,155} driving the wildfire increase.^{7,153} Tree death across the western United States doubled from 1955 to 2007¹⁴⁶ likely due to increased heat,²¹ wildfire,⁷ and bark beetle infestations,^{148,149} all of which are mainly attributable to climate change^{7,148,149} more than to other factors such as fire exclusion or competition for light and water.¹⁴⁶ In the Yosemite National Park biome shift,²⁰⁹ the research analyzed the relative contributions of temperature, precipitation, and the Pacific Decadal Oscillation. The researchers found that “Minimum temperature was the main effect related to accelerating annual branch growth in krummholz whitebark pine and initiation of pine invasion into formerly persistent snowfield openings.” In the Yosemite National Park small mammal range shift,²¹⁰ the locations of the monitoring sites allowed relative isolation of climate change factors. Moritz et al. (2008)²¹⁰ state, “The transect spans YNP [Yosemite National Park], a protected landscape since 1890, and allowed us to examine long-term responses to climate change without confounding effects of land-use change, although at low to mid-elevations there has been localized vegetation change relating to seral dynamics, climate change, or both.”

Cutting emissions through energy conservation and renewable energy can reduce ecological vulnerabilities. Under high emissions, projected climate change could triple burned area in the Sierra Nevada, but under low emissions, fire could increase just slightly.¹⁷³ Projections of biome shifts^{213,215} and wildlife range shifts^{217,218,219,220,221} consistently show lower vulnerabilities with lower emissions. Extensive research on, and practice of, fire management show that allowing naturally ignited fires to burn in wilderness and using low-severity prescribed burns can reduce fuels and the risk of high-severity fires under climate change.^{181,182,183} Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires.^{187,188,190,191} Numerous research results have identified climate change refugia for plants and animals.^{207,482,483}

Major uncertainties

Because climate model projections often diverge on whether precipitation may increase or decrease, two broad types of fire futures¹⁵² could be 1) dry-fire future—hotter and drier climate, increased fire frequency, fire limited by vegetation, potential biome change of forest to grassland after a fire due to low natural regeneration, and high carbon emissions; or 2) intense-fire future—hotter and wetter climate, more vegetation, increased fire frequency and intensity, fire limited by climate, and higher carbon emissions. These two broad categories each encompass a range of fire conditions. On the ground, gradients of temperature, precipitation, and climate water deficit (difference between precipitation and actual evapotranspiration) generate gradients of fire regimes. Because climate change, vegetation, and ignitions vary across the landscape, potential fire frequency shows high spatial variability. Therefore, future fire types could appear in patches across the landscape, with different fire future types manifesting themselves in adjacent forest patches. Changes in aridity may shift some plant and animal species ranges downslope to favorable combinations of available moisture and suitable temperature, rather than upslope.⁴⁸⁴ Plants and animals may respond to changing climate, and have been shown to do so, through range shifts, phenology shifts, biological evolution, or local extirpation. Thus, no single expected response pattern exists.²²⁴

Description of confidence and likelihood

Field evidence provides *high confidence* that human-caused climate change has increased wildfire, tree death, and species range shifts. Projections consistently indicate that continued climate change under higher emissions could increase the future vulnerability of ecosystems, but that reducing emissions and increasing fire management would reduce the vulnerability, providing *high confidence* in positive benefits of these actions.

Key Message 3

The Coast

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

Description of evidence base

At the Golden Gate Bridge, San Francisco, sea level rose 9 ± 0.4 inches (22 ± 1 cm) from 1854 to 2016,²³⁶ and at San Diego, 9 ± 0.8 inches (24 ± 2 cm) from 1906 to 2016.²³⁷ Analyses of these gauges and hundreds around the world show a statistically significant increase in global mean sea level^{238,239} due to melting of land ice and expansion of warming water caused by climate change.^{21,240} Measurements of sea surface temperatures from buoys off the California coast and around the world, combined with remote sensing data, have found warming of the top 75 m of ocean water at a rate of $2 \pm 0.4^\circ\text{F}$ ($1.1 \pm 0.2^\circ\text{C}$) per century from 1971 to 2010,²⁵² caused by climate change.²¹ Measurements and modeling of ocean acidity found an increase of acidity in the Pacific Ocean off San Diego of 25% to 40% (0.1 to 0.15 pH units) since 1750,⁴⁸⁵ caused by the increase of carbon dioxide

in the atmosphere from cars, power plants, deforestation, and other human activities.²¹ Measurements along the California coast have found ocean acidity during the core upwelling season (April to October) increasing by as much as four times (0.7 pH units) to some of the most acidic values in the world.²⁷⁴ Griggs et al. (2017)²⁴² project a median sea level rise of 19 inches (49 cm) and a range of 12–29 inches (30–73 cm; 67% probability) for the very low scenario (RCP2.6) and a median of 30 inches (76 cm) and a range of 19–41 inches (49–104 cm; 67% probability) for the higher scenario (RCP8.5) by the end of the century. On a similar timescale, Sweet et al. (2017)²⁴¹ provide one map showing sea level rise projections for San Francisco, which shows a 39–47 inch (1–1.2 m) rise for the Intermediate scenario (approximately RCP8.5); the range for all of their scenarios is 0.3–2.5 m. Jevrejeva et al. (2016)⁴⁸⁶ project a sea level rise of 73 cm and a range of 12–74 inches (37–187 cm; 5% probability) for the higher scenario (RCP8.5) by 2100.

Major uncertainties

Catastrophic rapid loss of Antarctic and Greenland ice sheets could increase sea level more rapidly. Sea level rise at individual locations depends on the form of the seafloor (bathymetry) and other local conditions. Climate change impacts compound overfishing and make fish populations more vulnerable. Potential economic changes in California's coastal and marine-based economies are subject to many different environmental and socioeconomic factors.

The full complexity of ecological responses to ocean acidification in combination with other stresses in California marine waters is currently unknown. Food supply for marine species,⁴⁸⁷ natural variation in resilience,^{488,489} and other environmental factors can affect the sensitivity of organisms to acidic conditions.

Description of confidence and likelihood

Field measurements at numerous locations have detected sea level rise, ocean warming, ocean acidification, and ocean hypoxia. Multiple model-based analyses have attributed these changes to human-caused climate change, giving *high confidence* to these impacts of climate change.

Key Message 4

Indigenous Peoples

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

Description of evidence base

Abundant evidence and strong agreement among sources exist regarding current impacts of climate change in the region. Impacts of climate change on the food sources, natural resources-based livelihoods, cultural resources and practices, and spiritual health and well-being of Southwest Indigenous peoples are supported, in part, by evidence of regional temperature

increases,^{23,24} drought,^{14,56,58,480} declines in snow,^{46,49,156} and streamflow,^{11,13,60,110} which have affected ecological processes, such as tree death,¹⁴⁶ fire occurrence,^{7,152} and species ranges.²¹¹

Impacts specific to Indigenous peoples include: 1) declining surface soil moisture, higher temperatures, and evaporation converge with oak trees' decreased resilience,²⁸⁵ diminished acorn production, and fire and pest threat to reduce the availability and quality of acorns for tribal food consumption and cultural purposes;³⁰⁶ and 2) declining vegetation, higher temperatures, diminished snow, and soil desiccation have caused dust storms and more mobile dunes on some Navajo and Hopi lands, resulting in damaged infrastructure and grazing lands and loss of valued native plant habitat.^{44,301,490} Evidence and agreement among evidence exist on the effects of climate-related environmental changes on culturally important foods,^{318,319} practices, and mental and spiritual health.⁴²

Multiple projections of climate and hydrological changes show potential future change and disruption to the ecosystems on which Indigenous peoples depend for their natural resources-based livelihoods, health, cultural practices, and traditions. These include projections of increased temperatures and heat extremes;²⁴ longer, more severe, and more frequent drought;^{13,65} expanded forest mortality;^{197,198} increased wildfire;¹⁷² and ocean temperature increases, ocean acidification, and inundation of coastal areas.^{242,273}

Evidence of specific future disruptions to traditional food sources from forests and oceans mostly relies upon inferences, based on projections of changing seasonality and associated phenological or ecosystem responses^{298,307} or potential changes to biophysical factors, such as salinity of freshwater lakes, and associated impacts to culturally important fish species.³¹⁰

Abundant evidence exists of autonomous adaptation strategies, projects, and actions, rooted in traditional environmental knowledge and practices or integration of diverse knowledge systems to inform ecological management to support adaptation and ecosystem resilience.^{490,491,492,493}

In response to the current and future projected climate changes and ecosystem disruptions, a number of tribes in the Southwest are planning and implementing energy efficient and renewable energy projects.^{327,361,494,495} These include installation of or planning for photovoltaic systems,³⁶¹ solar arrays, biofuels, microgrids, utility-scale wind, biogas, geothermal heating and cooling systems,³²⁷ increased building insulation,⁴⁹⁵ and carbon offsets.³³⁴ Several Southwest tribes, such as the Ramona Band of Cahuilla and the Santa Ynez Band of Chumash Indians, have established or are in the process of establishing energy independence.⁴⁹⁵ A well-recognized example is that of the Blue Lake Rancheria Tribe, in California, which was named a Climate Action Champion in 2015–2016 for implementing innovative climate actions, such as an all-of-the-above renewable strategy of transportation, residential, and municipal renewable energy projects, which includes a biogas project. A number of these projects (Ch. 15: Tribes, Figure 15.1) aim to simultaneously meet mitigation and adaptation objectives, such as the Yurok Tribe and the Round Valley Indian Tribe, which have developed carbon offset projects under California's cap-and-trade program to support tribally led restoration and stewardship.⁴⁹⁶

Several tribes in the Southwest are developing climate change adaptation plans to address the current climate-related impacts and prepare for future projected climate changes. The Santa Ynez Band of Chumash Indians, which is working towards an integrated energy and climate action plan,

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

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting Indigenous peoples in the Southwest include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) the way snow is treated in regional modeling,⁴⁹⁸ 3) variability in projections of extreme precipitation, and, in particular, 4) uncertainties in summer and fall precipitation projections for the region.⁸⁸ Additional uncertainties exist in sea level rise projections²⁴² and, for the California coast, ocean process model projections of acidification, deoxygenation, and warming coastal zone temperatures.⁴⁹⁹ For the most part, Native lands lack instrumental monitoring for weather and climate, which is a barrier for long-term climate-related planning.⁴⁹³

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

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

Description of confidence and likelihood

The documented human-caused increase in temperature is a key driver of regional impacts to snow, soil moisture, forests, and wildfire, which affect Indigenous peoples, other frontline communities, and all of civil society. Case study evidence, using Indigenous and Western scientific observations, oral histories, traditional knowledge and wisdom (e.g., Ferguson et al. 2016⁴⁹³), suggests that climate change is affecting the health, livelihoods, natural and cultural resources, practices, and spiritual well-being of Indigenous communities and peoples in the Southwest (e.g., Redsteer et al. 2011, 2013; Wotkyns 2011; Cozzetto et al. 2013; Gautam et al. 2013; Navajo Nation Department of Fish and Wildlife 2013; Nania and Cozzetto et al. 2014; Sloan and Hostler 2014; Redsteer and Fordham 2017^{44,302,305,307,310,311,490,500,501}). Abundant evidence gives *high confidence* that hotter temperatures, tree mortality, and increased wildfire and drought, due to climate change, would disrupt the ecosystems on which Indigenous people depend; the likelihood of these impacts affecting individual tribes will depend in large part on the non-climatic stresses (such as historical legacies and resource management practices) interacting with the climatic stresses. *Very high confidence* exists that tribes are developing adaptation measures and emissions reductions to address current and future climate change, based on abundant ongoing initiatives and associated documentation.

Key Message 5

Energy

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

Description of evidence base

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

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

Fossil fuel generation efficiency depends on the temperature and availability of the external cooling water. Warming could reduce energy efficiency up to 15% across the Southwest by 2100.⁹¹ Higher temperatures also increase electric resistance in transmission lines, causing transmission losses of 7% under higher emissions.³⁴⁴ Replacing fossil fuel generation with solar power renewables reduces greenhouse gas emissions and water use per unit of electricity generated.⁹⁰ This supports the assertion that increasing solar energy generation in the Southwest could meet the energy demand no longer being met by hydropower and fossil fuel as well as the expected increase in energy use in the future.

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

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

Solar and renewable energy jobs are increasing. The solar workforce increased 25% in 2016, while wind employment increased 32%.⁵⁰⁵ Jobs in low-carbon-emission generation systems, including renewables, nuclear, and advanced low-emission natural gas, comprise 45% of all the jobs in the

electric power generation and fuels technologies.⁵⁰⁵ Growing Southwest energy use, competitive prices for renewables, and the renewable energy potential of the Southwest favor the replacement of fossil-fuel-generated energy by renewable solar and wind energy.

Major uncertainties

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

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

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

Description of confidence and likelihood

Hydrological drought in California reduced hydroelectric generation³³⁵ and fossil fuel electricity generation efficiencies. Drought and rising temperatures under climate change can reduce the ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest (*very likely, very high confidence*). Renewable solar and wind energy offers increased electricity reliability, lower water intensity for energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely, high confidence*).

Key Message 6

Food

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

Description of evidence base

Climate change has altered climate factors fundamental to food production and rural livelihoods in the Southwest. Abundant evidence and good agreement in evidence exist regarding regionally increasing temperatures, reduced soil moisture, and effects on regional snowpack and surface water sources.^{13,23,67,74,79} The heat of climate change has intensified severe droughts in California^{14,56}

and the Colorado River Basin.¹³ Hotter temperatures and aridity in the Southwest affected agricultural productivity from 1981 to 2010.³⁶⁶

Elevated temperatures can be associated with failure of some crops, such as warm-season vegetable crops, and reduced yields and/or quality in others.³⁷⁴ Temperatures in California, Nevada, and Arizona are already at the upper threshold for corn³⁷² and rice.³⁷³ While crops grown in some areas might not be viable under hotter conditions, other crops such as olives, cotton, kiwi, and oranges may replace them.³⁷⁵ In the Southwest, climate change may cause a northward shift in crop production, potentially displacing existing growers and affecting rural communities.³⁷⁶ Quality of specialty crops, both nutritive and sensory, declines because of increased temperatures and other changes associated with a changing climate,^{393,511} which is particularly important in a region producing a majority of the Nation's specialty crops. Decreases in winter chill hours may reduce fruit and tree nut yields, though the magnitude may vary considerably.^{380,381}

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

Local-scale impacts can vary considerably across the region depending upon surface and groundwater availability. Drought causes altered water management, with heavy reliance on a limited groundwater to sustain regional food production.¹³⁰ Despite severe localized impacts, losses in total agricultural revenue are buffered by groundwater reliance to offset surface water shortage.³⁶⁹ Parts of the Southwest have exhausted sustainable use of groundwater resources. When surface water supplies are reduced, farmers shift to increased groundwater pumping, even when pumping raises production costs³⁷¹—declining groundwater tables significantly increase pumping costs and require drilling of deeper wells.¹³⁰ Continued climate change may reduce aquifer recharge in the southern part of the region 10%–20%.³⁷⁰ Climate change is projected to cause longer and more severe drought periods that will intensify the uncertainty associated with Southwest water supply and demand. Water-intensive forage crops and the livestock industry are especially vulnerable to climate-related water shortages.¹⁵

Major uncertainties

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

Since food security relies on complex national and international trade networks, how regional climate change may affect local food security is uncertain. Many adaptation options, such as using

alternate breeds, crops, planting and harvest dates, and new (sometimes untested) chemicals, may work in certain situations but not others. Thus, predicting impacts to food production in a hotter/drier land is likely to vary by crop and location, necessitating flexibility and adaptive management. Of paramount uncertainty is the impact of water shortage on regional food production as other uses may outcompete producers for limited supplies.

Description of confidence and likelihood

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

Key Message 7

Human Health

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

Description of evidence base

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

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

Good agreement exists among models that most of the Southwest may become more arid, due to the effect of increasing temperatures on snow, evaporation, and soil moisture.^{58,65,70,80} Projections also indicate that flood-causing atmospheric rivers may become more moist, frequent, and intense^{84,85,86} and that intense daily precipitation may increase in frequency.^{88,513} Models project

declines in future runoff of key Southwest rivers, such as the Colorado, due chiefly to the effects of increased temperature on soil moisture and snowpack.^{13,71,110}

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

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

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

Major uncertainties

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

Studies of non-fatal illnesses using healthcare services data can yield critical insights different from those one can derive from death data. Most studies of heat impacts on health have focused on deaths rather than nonfatal illnesses. This is primarily because hospitalization and emergency department data, compared with death certificate data, are not as available or uniform across locations, and when they are available it can be difficult to access them due to concerns for patient confidentiality. Ongoing enhancements to electronic medical records technology and

adoption across the healthcare services sector will potentially address those limitations in the near future and will provide invaluable data resources to identify and adopt prevention strategies that reduce the vulnerability of patients and populations to the adverse effects of climate-sensitive exposures.

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

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

Description of confidence and likelihood

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

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

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

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

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

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Federal Coordinating Lead Author**Steve T. Gray**

U.S. Geological Survey

Chapter Lead**Carl J. Markon**

U.S. Geological Survey (Retired)

Chapter Authors**Matthew Berman**

University of Alaska Anchorage

Jeremy Littell

U.S. Geological Survey

Laura Eerkes-Medrano

University of Victoria

Molly McCammon

Alaska Ocean Observing System

Thomas Hennessy

U.S. Centers for Disease Control and Prevention

Richard Thoman

National Oceanic and Atmospheric Administration

Henry P. Huntington

Huntington Consulting

Sarah Trainor

University of Alaska Fairbanks

Review Editor**Victoria Herrmann**

The Arctic Institute

Technical Contributors are listed at the end of the chapter.

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Key Message 1

Anchorage, Alaska

Marine Ecosystems

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

Key Message 2

Terrestrial Processes

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

Key Message 3

Human Health

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

Key Message 4

Indigenous Peoples

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

Key Message 5

Economic Costs

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

Key Message 6

Adaptation

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

Executive Summary



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

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

As the climate continues to warm, there is likely to be a nearly sea ice-free Arctic

during the summer by mid-century. Ocean acidification is an emerging global problem that will intensify with continued carbon dioxide (CO₂) emissions and negatively affects organisms. Climate change will likely affect management actions and economic drivers, including fisheries, in complex ways. The use of multiple alternative models to appropriately characterize uncertainty in future fisheries biomass trajectories and harvests could help manage these challenges. As temperature and precipitation increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost is expected to continue, with associated impacts to infrastructure, river and stream discharge, water quality, and fish and wildlife habitat.

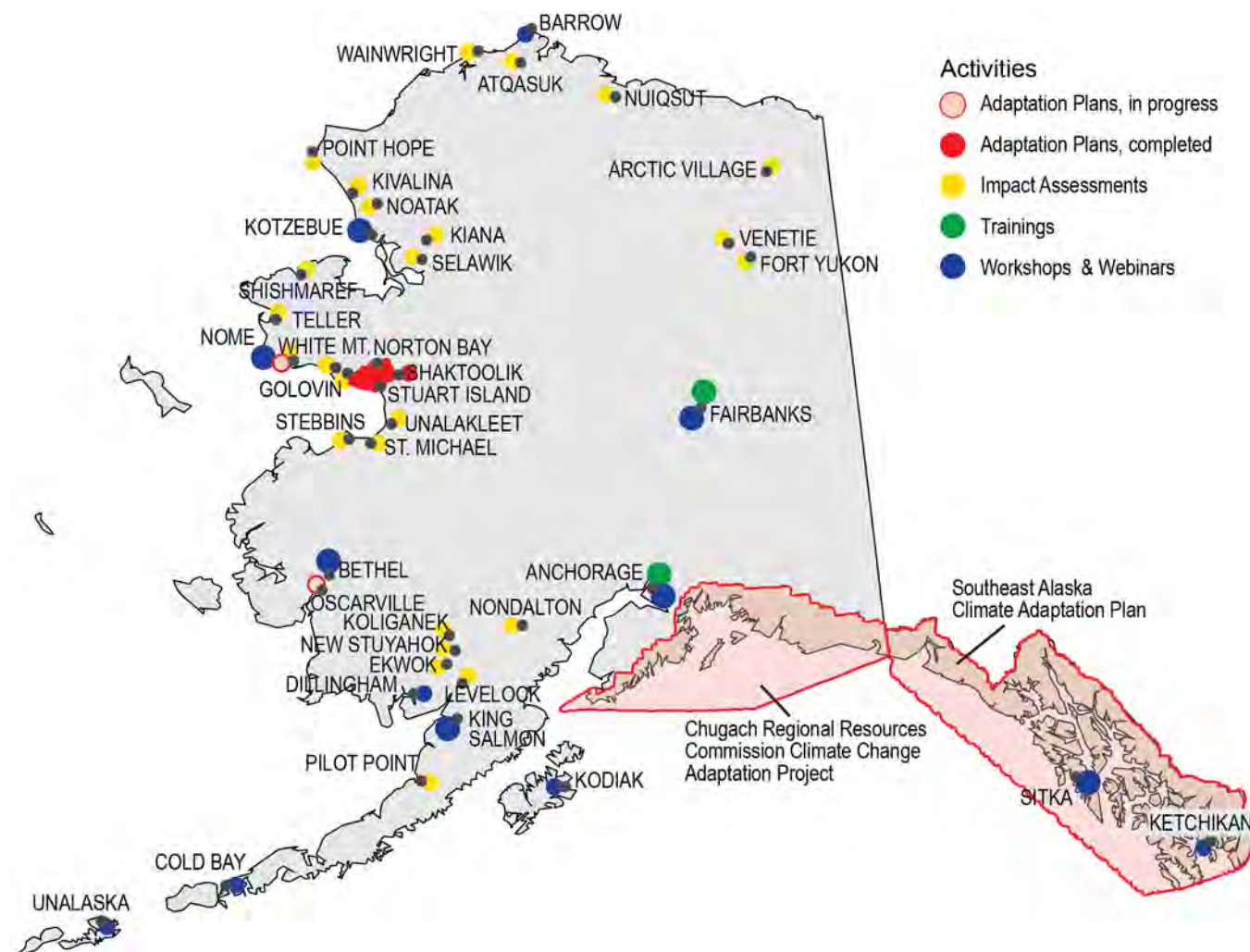
Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat in the future and in some cases requiring entire communities or portions of communities to relocate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

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

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

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

Adaptation Planning in Alaska



The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.^{1,2} Alaska is scientifically data poor, compared to other Arctic regions.³ In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;⁴ the University of Alaska for invasive species;⁵ and the Alaska Native Tribal Health Consortium for local observations of environmental change.⁶ Additional examples of community-based monitoring can be found through the website of the [Alaska Ocean Observing System](#).⁷ From Figure 26.9 (Source: adapted from Meeker and Kettle 2017⁸).

Background

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

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

Thawing permafrost, melting glaciers, and the associated effects on Alaska's infrastructure and hydrology are also of concern to Alaskans. Thawing permafrost has negatively affected important infrastructure, which is costly to repair, and these costs are projected to increase.^{20,21} Melting glaciers may affect

hydroelectric power generation through changes in river discharge and associated changes in reservoir capacity.²² A warming climate is also likely to increase the frequency and size of wildfires, potentially changing the type and extent of wildlife habitat favorable for some important subsistence species.^{23,24,25} Climate change also brings a wide range of human health threats to Alaskans due to increased injuries, smoke inhalation, damage to vital infrastructure, decreased food and water security, and new infectious diseases.¹⁰ The subsistence activities of local residents are also affected, which in turn affects food security, culture, and health.^{26,27,28,29}

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

Climate

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

Statewide annual average temperatures from 1925 to the late 1970s were variable with no clear pattern of change;³⁶ however, beginning in the late 1970s and continuing at least through the end of 2016, Alaska statewide annual average temperatures began to increase, with an average rate of 0.7°F per decade, (Taylor et al. 2017,³⁷ after Hartmann and Wendler 2005;³⁸ see Figure 26.1). Temperatures have been increasing faster in Arctic Alaska than in the temperate southern part of the state, with the Alaska North Slope warming at 2.6 times the rate of the continental U.S. and with many other areas of Alaska, most notably the west coast, central interior, and Bristol Bay, warming at more than twice the continental

U.S. rate.³⁹ The long-term temperature trends, however, include considerable variability from decade to decade. For example, in the early part of the record (1920s to early 1940s), temperatures were moderate statewide, with annual averages generally near the long-term average, but were lower from about 1945 to about 1976 and then increased rapidly in the 1970s and 1980s and again in the mid-2010s (Figure 26.1). These variations are in part consistent with variations in large-scale patterns of climate variability in the Pacific Ocean;⁴⁰ in particular, Arctic warming in the early 20th century was intensified by Pacific variability (warm and cold anomalies of the Pacific sea surface temperatures).⁴¹ Precipitation changes have

Observed and Projected Changes in Annual Average Temperature

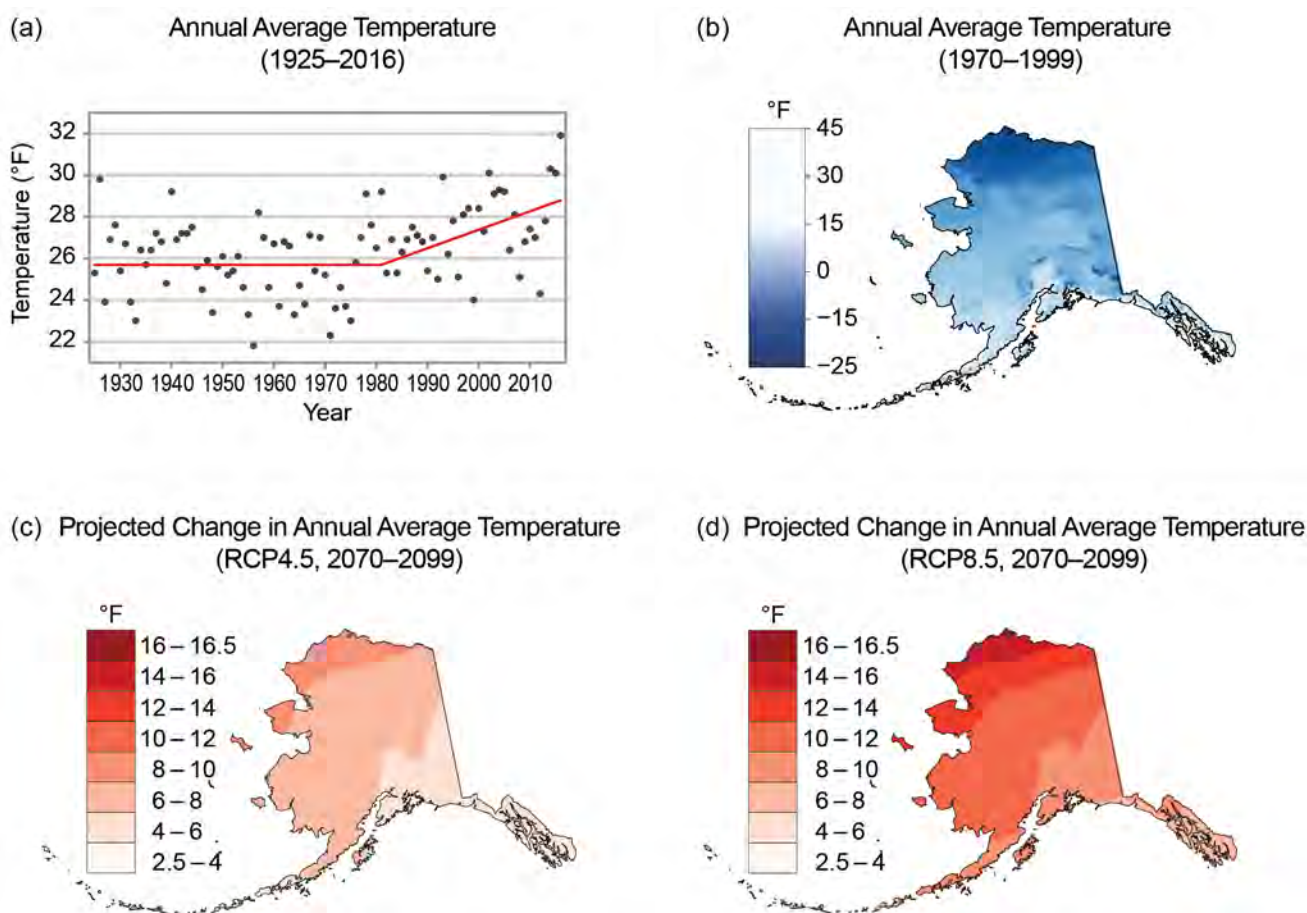


Figure 26.1: (a) The graph shows Alaska statewide annual average temperatures for 1925–2016. The record shows no clear change from 1925 to 1976 due to high variability, but from 1976–2016 a clear trend of +0.7°F per decade is evident. (b) The map shows 1970–1999 annual average temperature. Alaska has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

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

Projected Temperature and Precipitation Changes

Recent availability of more localized climate information allows for more complete descriptions of the geographical variation in historical trends and climate projections.^{39,42,43} Using downscaled global climate models⁴³ and the higher scenario (RCP8.5) (see Ch. 2: Climate, Box 2.7 and the Scenario Products section of App. 3),⁴⁴ more warming is projected in the Arctic and interior areas than in the southern areas of Alaska, and average annual precipitation increases are projected for all areas of the state, with greater increases in the Arctic and interior and the largest increases in the northeastern interior.

Climatic extremes are expected to change with the changing climate. Under a higher scenario (RCP8.5), by mid-century (2046–2065) the highest daily maximum temperature (the hottest temperature one might expect on a given summer day) is projected to increase 4°–8°F compared to the average for 1981–2000. For the same future period (2046–2065), the lowest daily maximum temperature (the highest temperature of the coldest day of the year) throughout most of the state is projected to increase by more than 10°F, with smaller projected changes in the Aleutian Islands and southeastern Alaska. Additionally, the lowest daily minimum temperatures (the coldest nights of the year) are projected to increase by more than 12°F. The number of nights below freezing would likely decrease by at least 20 nights per year statewide, and by greater than 45 nights annually in coastal areas of the North Slope, Seward Peninsula, Yukon–Kuskokwim Delta, Alaska Peninsula, and Southcentral Alaska.⁴⁵ Annual maximum one-day precipitation is projected to increase by 5%–10% in

southeastern Alaska and by more than 15% in the rest of the state, although the longest dry and wet spells are not expected to change over most of the state.⁴⁵ Growing season length (the time between last and first frosts in a given year) is expected to increase by at least 20 days and perhaps more than 40 days compared to the 1982–2010 average.³⁵ Whether or not this increased growing potential is realized will largely depend on soil conditions and precipitation.

Key Message 1

Marine Ecosystems

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

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

Arctic Sea Ice Continues to Change

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

Sea ice provides an important surface for algal production and growth in marine ecosystems during spring. This production beneath the sea ice is an important source of carbon for pelagic (mid- to upper-water column) grazers, such as copepods and krill, and for benthic (lower-water) detritivores, such as clams and worms that feed on dead, organic material.^{47,48} In turn, the abundance of these animals provides food for higher trophic-level organisms such as fish, birds, and mammals in regional marine ecosystems. The presence or absence

of sea ice affects the transfer of heat, water temperature, and nutrient transport, as well as other processes (such as the breakdown or transformation of organic matter into its simplest inorganic forms) that affect ecosystem productivity.⁴⁹ In the Arctic, higher-level organisms such as Arctic cod,¹⁷ polar bears, and walrus^{50,51,52,53} are dependent upon sea ice for foraging, reproduction, and resting and are directly affected by sea ice loss and thinning (Box 26.1).

Box 26.1: Polar Bears and Walrus

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



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

Ocean Acidification

The oceans are becoming more acidic (known as ocean acidification) in an emerging global problem that will intensify with continued carbon dioxide (CO₂) emissions (Ch. 9: Oceans, KM 1 and 2). Ocean acidification negatively affects organisms such as corals, crustaceans, crabs, mollusks, and other calcium carbonate-dependent organisms such as pteropods (free-swimming pelagic sea snails and sea slugs), the latter being an important part of the food web in Alaska waters. Some studies in the nutrient-rich regions have found that food supply may play a role in determining the resistance of some organisms to ocean acidification.⁵⁴

Changes in ocean chemistry and increased corrosiveness are exacerbated by sea ice melt, respiration of organic matter, upwelling, and glacial runoff and riverine inputs, thus making the high-latitude North Pacific and the western Arctic Ocean (and especially the continental shelves of the Bering, Chukchi, and Beaufort Seas; see Figure 26.3) particularly vulnerable to the effects of ocean acidification. Also, more ice-free water will indirectly allow for greater uptake of atmospheric CO₂.^{18,55,56} More recent research suggests that corrosive conditions have been expanding deeper into the Arctic Basin over the last several decades.⁵⁷ The annual average aragonite saturation state (a metric used to assess ocean acidification) for the Beaufort Sea surface waters likely crossed the saturation horizon near 2001),¹⁸ meaning that the Beaufort Sea is undersaturated (lacking sufficient concentrations of aragonite) most of the year—a condition that limits the ability of many marine species to form shells

or skeletons (Figure 26.3). Under the higher scenario (RCP8.5), the Chukchi Sea is projected to first cross this threshold around 2030 and then remain under the threshold after the early 2040s, and the Bering Sea will likely cross and remain under the threshold around 2065 (Figure 26.3).¹⁸

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

Projected Changes in Arctic Ocean Acidity

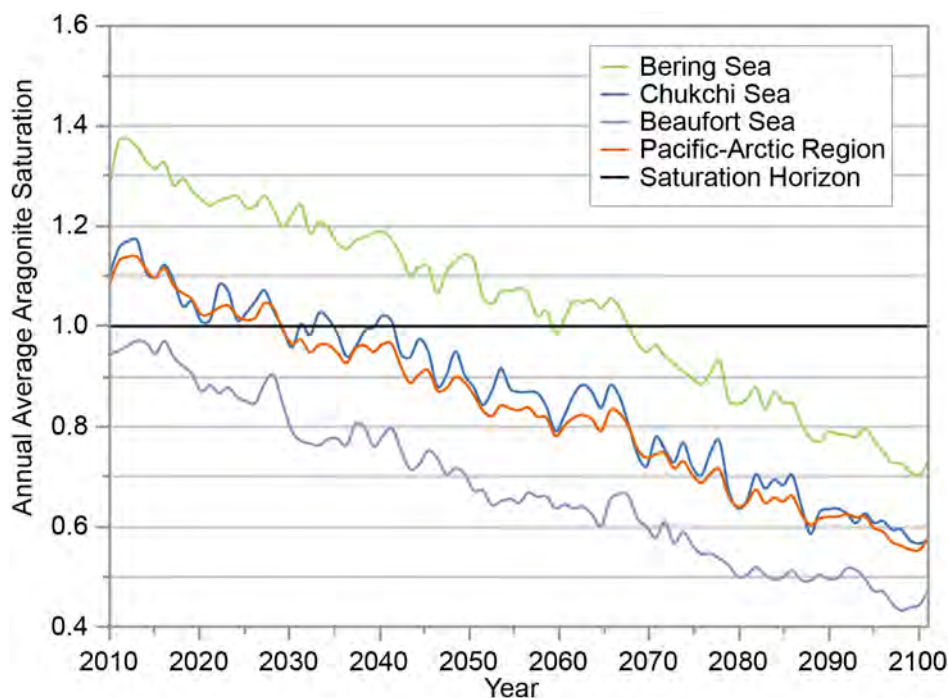


Figure 26.3: The time series shows the projected decline in the annual average aragonite saturation (one of the consequences of increased ocean acidity, or lower pH) for the Bering Sea, Chukchi Sea, Beaufort Sea, and for the entire Pacific-Arctic region under the higher scenario (RCP8.5). Aragonite saturation is a metric used to assess ocean acidification and the ability for organisms to build shells and skeletons. The annual average saturation state for the Beaufort Sea surface waters likely crossed the saturation horizon—a tipping point—around 2001, meaning it is currently undersaturated and its marine ecosystems are vulnerable to the impacts of ocean acidification during most of the year. The Chukchi Sea is projected to first cross this threshold around 2030 and then likely remain under the threshold after the early 2040s; the Bering Sea is projected to be a concern after 2065. Source: adapted from Mathis et al. 2015.¹⁸

Alaska Fishes

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

The distribution of many ocean fish species is shifting northward as the ranges of warmer-water species expand and colder-water species contract in response to rising ocean

temperatures (Ch. 9: Oceans, KM 2), with the confirmed presence of 20 new species and 59 range changes in the last 15 years in the Chukchi and Beaufort Seas.¹⁷ In the Bering Sea, Alaska pollock, snow crab, and Pacific halibut have generally shifted away from the coast and farther from shore since the early 1980s.⁷⁵ These changes reflect possible northward shifts in species distributions, particularly in the Bering Strait region.⁷⁶

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

Changes to North Pacific Marine Ecosystems in a Warming Climate

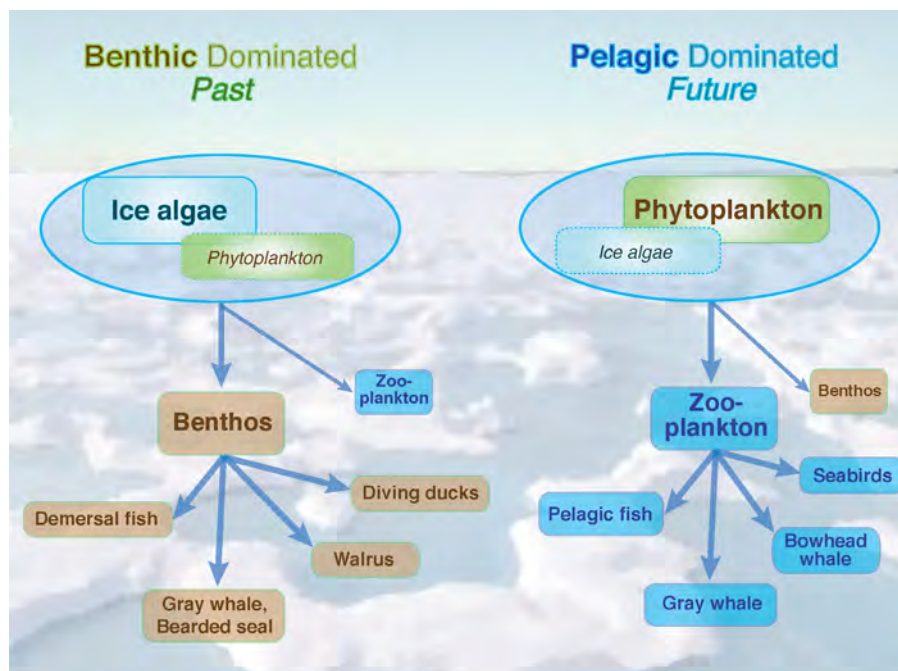


Figure 26.4: As sea ice thins and retreats earlier in the season, it is anticipated that food webs under the ice will switch from a benthic-dominated (lower in the water to seafloor) to a pelagic-dominated (middle to higher in the water) marine ecosystem. Source: Moore and Stabeno 2015.⁷⁸

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

populations, a keystone species in Chukchi and Beaufort Seas food webs.¹⁷

Changes in climate-related events are likely to affect management actions and economic drivers, including fisheries, in complex ways.⁸⁰ An example is the recent heat wave in the Gulf of Alaska, which led to an inability of the fishery to harvest the Pacific cod quota in 2016 and 2017 and to an approximately 80% reduction in the allowable quota in 2018.⁸¹ These reductions are having significant impacts on Alaska fishing communities and led the governor of Alaska to ask the Federal Government to declare a fisheries disaster. Events such as these are requiring the use of multiple, alternative models to appropriately characterize uncertainty in future population trends and fishery harvests.⁸² The need to address uncertainty is especially true for the Eastern Bering Sea pollock fishery, which is one of the largest in the United States.⁸³ While most scientists agree that walleye pollock populations in the eastern Bering Sea are likely to decrease in a warming

climate,^{84,85,86,87,88} these effects can be mitigated to some extent by adopting alternative fish harvest strategies,⁸⁹ and economic losses may be partially offset by increased pollock prices.⁹⁰

Key Message 2

Terrestrial Processes

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

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

associated runoff influences other terrestrial ecosystems.¹⁰¹

Permafrost

About half of Alaska is underlain by permafrost—an essential geographic quality that affects landscape patterns and processes,¹⁰² and construction in the Arctic depends on the ability of permafrost to remain frozen. Since the 1970s, Arctic and boreal regions in Alaska have experienced rapid rates of warming and thawing of permafrost,^{103,104,105,106} with spatial modeling¹⁰⁷ projecting that near-surface permafrost will likely disappear on 16% to 24% of the landscape by the end of the 21st century.¹⁰⁸ Confidence in these estimates is higher than for those in the Third National Climate Assessment¹⁰⁹ due to more field sample sites, higher resolution imagery for mapping, and advanced geographic modeling techniques.

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

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

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

Wildfire

The annual area burned by wildfires in Alaska varies greatly year-to-year, but the frequency of big fire years (larger than 2 million acres) has been increasing—with three out of the top four fire years (in terms of acres burned) in Alaska occurring since the year 2000.¹¹⁴ As a result, the vegetation of forested Interior Alaska now has less acreage of older spruce forest and more of post-fire early successional vegetation, birch, and aspen than it did prior to 1990.⁹⁵ This change favors shrub-adapted wildlife species such as moose but also destroys the slow-growing lichens and associated high-quality winter range that caribou prefer, though the effects of fire-driven habitat changes to caribou population dynamics are uncertain.²³ Some rural communities, however, have adapted to these vegetation changes by designing small-scale programs that enhance moose browsing (feeding on leaves, twigs, or tree branches) or developing biofuel infrastructure integrated with fire prevention tactics.^{115,116} In addition to range expansion due to changes in wildfire, shrubs have been increasing in density and height in tundra environments

due to increasing temperatures,⁹⁸ with shrub expansion in tundra ecosystems being observed across the North American Arctic.^{117,118} Shrub-adapted wildlife species such as moose and snowshoe hares, and in some cases beaver, have followed the expansion of shrubs and are now common in parts of Arctic Alaska and Canada, where they were previously rare or absent.^{24,119,120} The area burned by wildfires may increase further under a warming climate.²⁵ Projections of burned area for 2006–2100 are estimated at 98 million acres under a lower scenario (RCP4.5) and 120 million acres under a higher scenario (RCP8.5).

Coastal and River Erosion

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

Erosion Rates Along Alaska's North Coast

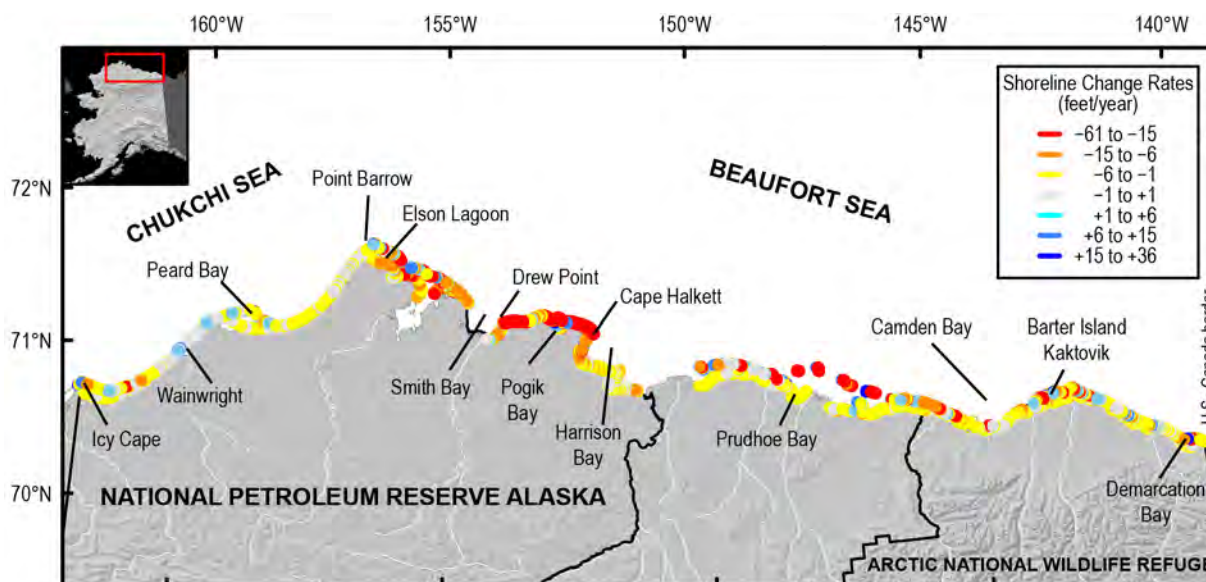


Figure 26.5: The map is of the north coast of Alaska and shows color-coded shoreline erosion rates, which can lead to the loss of habitat, cultural resources, and infrastructure. Source: adapted from Gibbs and Richmond 2015.¹⁹

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

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

Glacier Change

Glaciers continue to melt in Alaska, with an estimated loss of 75 ± 11 gigatons (Gt) of ice volume per year from 1994 to 2013,^{136,137} 70% of which is coming from land-terminating glaciers; this rate is nearly double the 1962–2006 rate.¹³⁸ Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,^{139,140,141,142} with the potential to alter streamflow along the Gulf of Alaska¹⁴³ and to change Gulf of Alaska nearshore food webs.¹⁴⁴

Melting glaciers are likely to produce uncertainties for hydrologic power generation,²² which is an important resource in Alaska.^{145,146} In the short term, melting glaciers can increase hydropower capacity by increasing downstream flow; however, with continued melting there will likely be less meltwater for the future. This may be offset by an increase in precipitation in Alaska,⁴⁵ although an increase in precipitation does not necessarily lead to increases in catchment runoff (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5).¹⁴⁷

Key Message 3

Human Health

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

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

Direct Exposures

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

Winter travel has long been a key feature of subsistence food gathering activities for rural Alaska communities. Higher winter temperatures and shorter durations of ice seasons may delay or disrupt usual patterns of ice formation on rivers, lakes, and the ocean. For hunters and other travelers, this increases the risk of falling

through the ice, having unplanned trip extensions, or attempting dangerous routes, leading to exposure injury, deaths, or drowning (Box 26.3).^{26,148} Community search and rescue workers experience similar risks in searching for missing travelers, extending the threat across communities. Adaptation strategies being promoted include improved communication about local ice and water conditions, increasing use of survival suits and personal floatation devices,¹⁴⁹ and the use of personal locator beacons and messaging devices that can alert responders to a traveler at risk or provide reassurance and avoid unneeded search and rescue operations in high-risk conditions.¹⁵⁰

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

Box 26.3: Climate Change and Public Health

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

- the One Health Group, which consists of federal, state, and nongovernmental organizations, conducts quarterly webinars and presentations on the intersection between human, animal, and environmental health. Cosponsored by the Centers for Disease Control and Prevention, this forum improves communication and situational awareness about climate change and public health in Alaska;¹⁵¹
- the Local Environmental Observer (LEO) Network,⁶ a forum funded by the Environmental Protection Agency, the Department of the Interior, and the Bureau of Ocean Energy Management, is used for tracking local observations of environmental events and connecting communities with technical resources using an internet-based mapping tool and smartphone applications;
- comprehensive climate vulnerability assessments of rural Alaska communities;¹⁵² and
- an electronic newsletter, *Northern Climate Observer*, which provides weekly access to articles and observations about the circumpolar north.¹⁵²

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

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

Climate-driven increases in air pollution in Alaska are primarily linked to the increases in wildfire frequency and intensity. Wildfires, however, threaten individual safety in adjacent communities and pose risks downwind from smoke inhalation, particularly for children and persons with chronic respiratory and cardiovascular conditions (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1).^{10,158} Adaptations to protect persons at risk from wildfire exposure include using community air quality indices

linked to recommendations for specific groups, educating people about outdoor activities and use of masks, and creating a “clean room” using high-efficiency particulate air (HEPA) dust filters or air conditioning.¹⁵⁹ It is also likely that there will be an increased risk of respiratory allergies related to longer and more intense seasonal pollen blooms and mold counts (Ch. 13: Air Quality, KM 3).¹⁶⁰ Public reporting of pollen counts conducted in Anchorage and Fairbanks¹⁶¹ is used to advise allergy sufferers of increasing risks and is linked to recommendations to avoid exposure and reduce symptoms. Increased respiratory symptoms have also been reported in communities that are experiencing

increased windblown dust. Adaptations include dust suppression, improving indoor air quality, and use of masks.

Indirect Effects

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

In-home water and sanitation services are a fundamental contributor to health, and the absence of such services in 15% of rural Alaska homes is associated with increased risk of gastrointestinal, respiratory, and skin infections.^{155,162,163} Climate-related environmental changes that can affect access to water and sanitation services have been well-documented.¹⁵⁴ These changes include loss of surface water through drainage of tundra ponds, lower source-water quality through increased riverbank erosion due to permafrost thaw or saltwater intrusion in coastal communities, and increased coastal erosion or storm surge leading to wastewater treatment system damage.¹⁶⁴ Permafrost thawing poses a threat to centralized water and wastewater distribution systems that need stable foundations to maintain system integrity. More flexible service connections have been used to reduce damage from movement caused by permafrost thawing.¹⁶⁵ People cope with water shortages by use of rainwater catchment or other untreated water sources, reuse of water used for clothes or personal hygiene, or rationing of water to prioritize drinking and cooking. Such practices, however, could lead to increased risk of waterborne infectious diseases or increased

spread of person-to-person infections through decreased hygiene. Increased silt or organic material in source water can quickly clog filters, increasing costs of water treatment. This can result in reduced filtration effectiveness and increased exposure to waterborne pathogens, such as *Giardia intestinalis*.¹⁶⁵ The state of Alaska is funding development and testing of decentralized water and sanitation systems that use in-home treatment, water reuse, and other efficiencies that may be an alternative in homes without existing services or if centralized systems fail.¹⁶⁶

Changes in insect and arthropod ranges due to climate change have raised human health concerns, such as the documented increase in venomous insect stings in Alaska.^{167,168}

Tick-borne human illnesses are uncommon in Alaska, but new reports of ticks on domestic dogs without travel exposure outside Alaska raise concerns about tick range extension into Alaska and the potential for introduction of new pathogens.¹⁶⁹ Several human infectious diseases could potentially expand in a changing Alaska climate. For example, climate change may allow some parasites to survive longer periods, provide an increase in the annual reproduction cycles of some disease-carrying insects and pests (vectors), or allow infected host animal species to survive winters in larger numbers, all increasing the opportunity for transmission of infection to humans.¹⁷⁰ However, some of these diseases are rare, and detecting increases is hampered by Alaska's small population, limited access to diagnostic testing, and the absence of surveillance for some human illness (for example, toxoplasmosis, an infection caused by a parasite). Foodborne pathogens, including parasites, have been identified as likely to increase due to increased temperature changes and increasing exposure.^{171,172} In Alaska, disruption of ice cellars from thawing permafrost and coastal erosion has raised concerns about food spoilage or

infectious outbreaks, but documented human illness events are lacking. Likewise, the documented northward range expansion of beavers has been postulated to increase the threat of waterborne *Giardia* infections in humans; however, human *Giardia* illness reports have been stable in Alaska and show no increasing regional trends.¹⁷³ Emerging infectious threats led to the formation of an Alaska One Health Group, which meets quarterly to combine perspectives from human, animal, and environmental health and uses new data generated from the Local Environmental Observer (LEO) Network.^{6,174} A new rural monitoring program has been developed for tribal community settings to include collection of data on infectious threats from food, animals, and water.¹⁷⁵

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

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

Psychological and Social Effects

Climate change is a common concern among Alaskans and is associated with feelings of depression and uncertainty about the potential changes to communities, subsistence foods, culture, and traditional knowledge and the potential of relocation from long-established traditional sites.¹²² These uncertainties and threats have effects on mental health and on family and community relationships and may lead to unhealthy responses such as substance abuse and self-harm.¹⁸⁰ This is especially true of Indigenous peoples, who have a deep connection to their home areas, often described as sense of place.^{181,182,183,184} Over generations,

Indigenous communities have developed extensive knowledge about their areas and the plants and animals with which they share an ecosystem.¹⁸⁵ As the effects of climate change are felt in the landscape, many Alaska Natives feel a sense of personal loss as the familiar has become unpredictable and sometimes strange.¹²⁵ This uncertainty has also reduced traditional camping activities that strengthen community ties. Damage or loss to cultural sites and properties is also a great concern, reducing the sense of cultural continuity in one's place along with information about living and adapting there. In the context of many other social, technological, economic, and cultural changes affecting Indigenous communities, the continuation of traditional activities in traditional places can be a bedrock of stability. When this, too, is threatened, a wider sense of environmental security is at risk.¹²⁵ Community relocation or the movement of persons away from climate-threatened areas can have intergenerational effects through loss of cultural connections and adverse childhood experiences leading to poorer health outcomes. The Alaskans most vulnerable to these climate-related changes are those who are most dependent on subsistence foods, the poor, the very young, the elderly, and those with existing health conditions that require ongoing care, that limit mobility, or that reduce capacity to accommodate changes in diet, family support, or stress.¹¹

Key Message 4

Indigenous Peoples

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

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

Subsistence Activities

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

these subsistence activities are conducted.^{15,182} Examples include

- reducing the presence of shore-fast ice used as a platform to hunt seals¹⁹⁴ or butcher whales,¹⁹⁵
- reducing the availability of suitable ice conditions for hunting seals and walrus (Figure 26.6),²⁸ and
- exacerbating the risks of winter travel due to increasing areas of thin ice and large fractures within the sea ice (commonly referred to as “leads”) as well as water on rivers.^{26,27,196}

However, climate change is also providing more opportunity to hunt from boats late in the fall season or earlier in spring.¹²⁵ Increasing temperatures affect animal distribution and can alter the availability of subsistence resources, often making hunting and fishing harder but sometimes providing new opportunities, such as fall whaling on St. Lawrence Island.¹⁹⁷ Shellfish populations, an important subsistence and commercial resource along the Alaska coast, have been declining for more than 20 years throughout coastal Alaska, with ocean warming and ocean acidification (Ch. 9: Oceans) contributing to the decline (see Key Message 1). Warm temperatures and increased

humidity are also affecting ice cellars used traditionally to store food (as noted earlier in this chapter), thereby making it harder to air-dry meat and fish on outdoor racks, causing food contamination.^{131,198} Some communities have found new storage methods or have changed to an increasingly Western diet. Subsistence foods decrease the costs of feeding a family compared to purchased foods, which in rural Alaska are almost twice the cost of those in Anchorage.^{199,200} One net result of all these changes is an overall decrease in food security for residents of rural Alaska Native communities (Ch. 10: Ag & Rural, KM 4).²⁹

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



Variable Weather Affects Harvest Levels

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

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

Adaptation Actions

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

Key Message 5

Economic Costs

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

Climate change in Alaska has caused regionally disparate economic effects. The infrastructure and community relocation costs, along with potential adverse effects on fisheries, accrue predominantly to rural communities. While both urban and rural communities benefit from reduced space heating costs, the urban communities bear few of the costs and risks. The profound and diverse climate-driven changes in Alaska's physical environment and ecosystems generate economic impacts through their effects on environmental services. These services include positive benefits directly from ecosystems (for example, food, water, and other resources), as well as services provided directly from the physical environment (for example, temperature moderation, stable ground for supporting infrastructure, and smooth surface for overland transportation).²¹³ Some of these effects are relatively assured and in some cases are already occurring. Other impacts are highly uncertain, due to their dependence on the structure of global and regional economies and future human alterations to the environment¹¹² decades into the future, but they could be large.

Infrastructure

Threats to infrastructure in Alaska from coastal and riparian erosion caused by the combination of rising sea levels, thawing permafrost,

reduced sea ice, and fall storms are well known.^{214,215} A study published in 2008 projected that the cost (for 2008–2030) associated with early reconstruction and replacement of public infrastructure (roads, public buildings, airports, and rail lines) caused by damage from these threats was estimated to be between \$3.6 and \$6.1 billion (in 2008 dollars).²⁰ Assuming the 2.85% annual real interest rate used in these studies, the cost translates to an average of \$250 to \$420 million per year (in 2015 dollars). A more recent study estimated a somewhat smaller annual cost of \$110–\$270 million between 2015 and 2060 for maintenance and repair costs to mitigate or remediate damage to public infrastructure from climate warming (in 2015 dollars, discounted 3%) under the lower scenario (RCP4.5) and higher scenario (RCP8.5), respectively.^{11,91} Projecting these costs to the end of the century, cumulative effects amounted to \$3.7 billion under the lower scenario (RCP4.5) to \$4.5 billion under the higher scenario (RCP8.5) for reactive repair and replacement, but \$2.0 to \$2.5 billion for proactive adaptation costs, depending on the climate change scenario¹¹ (in 2015 dollars, discounted 3%). The lower cost assumes that funding will be available for maintenance and repair before facilities require replacement, which is not guaranteed.^{216,217} Both studies excluded losses to commercial and industrial buildings and private homes.

Coastal and riverine erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.¹²³ Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office study ranged from \$80 to \$200 million per community (dollar year not reported).^{122,218} Beyond financial cost, additional challenges of relocation involve legal and policy

obstacles, as well as deep cultural ties to landscape and place. Construction of rock walls, use of sandbags and riprap,²¹⁹ and replacement infrastructure for communities that are partially relocated¹²³ represent additional costs, as would loss of productivity and income from lack of access to utilities and drinking water and temporary displacement of residents when water and sewer lines rupture.^{220,221,222}

Ice Road Transportation

In rural Alaska, where surface transportation infrastructure is extremely limited, snow and ice offer a low-cost alternative for moving people, goods, and heavy industrial equipment. As the climate warms, the resulting shorter and milder cold season reduces the season length for ice road use, increases the risk of travel on river ice, and increases the wear and tear on snow machines. Loss of overland winter transportation raises costs for extractive industries (such as oil extraction and logging) and rural Alaska households. A 2004 report estimated the cost of ice roads on the North Slope of Alaska at \$100,000 per mile, versus as much as \$2 million per mile for a gravel road (in 2003 dollars; \$127,000 per mile for ice roads and \$2.5 million for gravel in 2015 dollars).²²³ Costs of foregone economic activity¹⁰³ and increased risk of winter travel are more difficult to quantify.²²⁴

Marine Vessel Traffic

Reduced seasonal ice has been associated with increased marine traffic in the U.S. maritime Arctic.²²⁵ A longer ice-free shipping season could reduce the cost of shipping ore from the Red Dog mine and other mines in the region,^{154,226} as well as increase certainty of shipping production facilities and equipment to North Slope oil fields. Adverse navigability effects of reduced river discharge²²⁷ could offset beneficial effects of an extended ice-free shipping season on the cost of barge service to communities in western and northern Alaska.

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

Wildfire Costs

Increasing incidence of wildfire near inhabited areas leads to a wide array of costs, including firefighting costs, health and safety impacts, property damage, insurance losses, and higher costs of fire insurance (Figure 26.7).²³⁵ In addition, tourism businesses may experience short-term losses as visitors avoid recently burned areas. A recent estimate projected an increase in wildfire suppression costs of \$25 million more per year (in 2015 dollars, 3% discount rate) under the lower scenario (RCP4.5) above the 2002–2013 annual average by the end of the century.²¹ The cost could be higher if the footprint of human settlement expands and the geographic area designated for active fire suppression expands accordingly. Property



Wildfire Destroys Homes Near Willow, Alaska

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

damage from wildfires will likely increase as the number of large fire years increases. The Millers Reach Fire in 1996 destroyed 454 structures, including 200 homes in the Matanuska-Susitna Borough, with an estimated total cost of \$80 million (in 1996 dollars; \$120 million in 2015 dollars).²³⁶ A subsequent fire in 2015 in the same general area destroyed another 55 homes and heavily damaged 44 other structures.²³⁷

Heating Costs

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

Energy Needed for Heating Decreases Across Much of Alaska

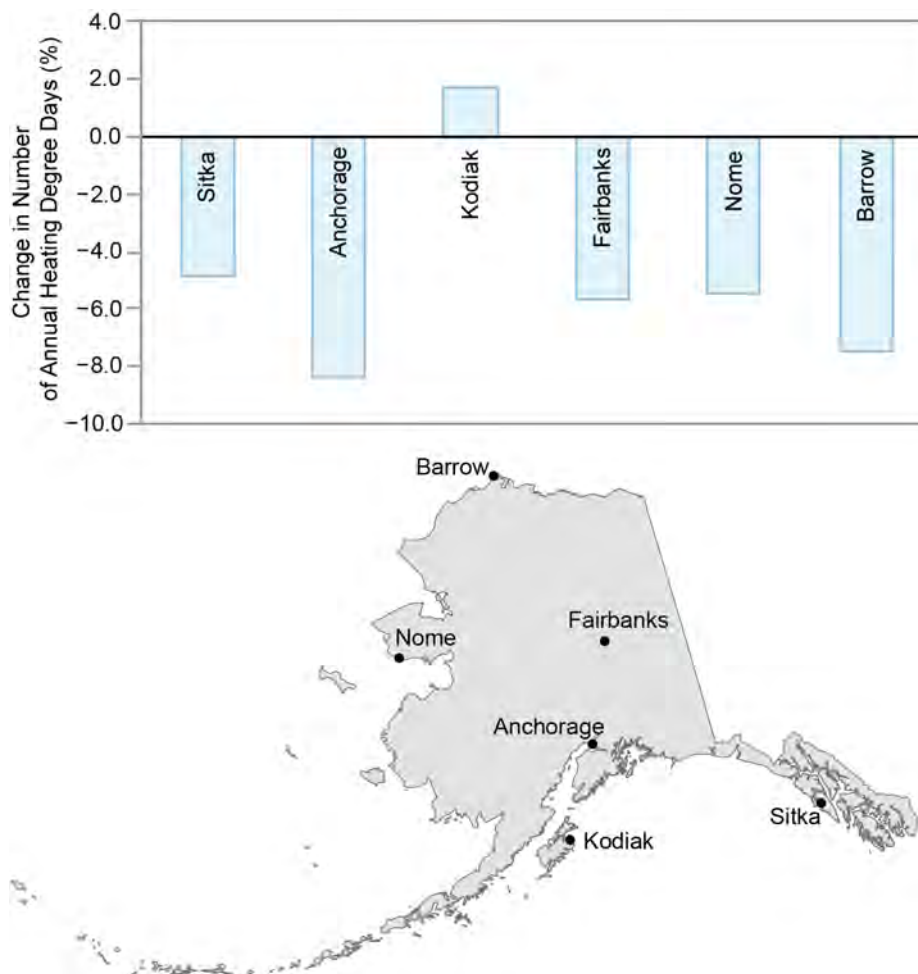


Figure 26.8: The chart shows the percentage change in annual heating degree days for the period 2000–2015 (as compared to 1950–1979) for six Alaska communities. Every 1% decline in heating degree days could potentially yield \$10 million of annual savings in heating costs. Sources: University of Alaska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

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

Key Message 6

Adaptation

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

Alaska and its adjacent Arctic areas are experiencing some of the largest climate changes in the United States (Ch. 2: Climate, KM 7).¹⁴ As such, residents, governments, and

industry must prepare for and adapt to the changing climate and associated environmental changes if the most severe impacts are to be avoided.^{187,188,241}

Adaptation is often defined as an adjustment in human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects²⁴² and is an iterative, ongoing process that involves assessment and redirection as needed (Ch. 28: Adaptation).²⁴³ Efforts to prepare for and adapt to the impacts of climate change in Alaska can reduce costs associated with the impacts of climate change,^{20,91} generate social and economic opportunities,^{244,245} and improve livelihood security.^{125,246,247,248} Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change²⁴⁹ and ocean acidification.²⁵⁰

Key elements of successful adaptation in Alaska include coordinated consideration of both environmental and social conditions¹³⁴ and careful attention to local context; there is no “one-size-fits-all” strategy.^{187,188,251} Enhanced communication, coordination, knowledge sharing, and collaboration are important components of adaptation in Alaska. This includes between communities, among scientists and communities, and across government bodies at the tribal, community, borough, state, and national levels.^{251,252,253,254,255,256,257} Building adaptation solutions in partnership with local knowledge is vital for ensuring that adaptations meet local needs and priorities.^{254,258,259,260,261}

A range of adaptations to changing climate and related environmental conditions are underway in Alaska, and others have been proposed as

potential actions.¹³⁵ These adaptations involve human health and poverty alleviation,^{136,188} livelihood security,¹²⁵ ecosystem management,²⁶² new construction designs for housing,²⁶³ and a host of other options.¹³⁵ Some of these measures reduce vulnerability and risk, while others involve more systemic institutional transformation.^{255,260}

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

Climate change action plans and vulnerability assessments have been completed by several municipalities in Alaska.¹³⁵ Formal tribal adaptation planning and preliminary planning activities such as workshops, trainings, webinars, monitoring, and vulnerability assessments have been conducted throughout the state. As of this writing, three climate adaptation plans have been completed and three additional projects are underway to produce climate adaptation plans (Figure 26.9).⁸ The Bureau of Indian Affairs awarded eight Climate Resilience Program Awards for adaptation planning between 2013 and 2019.⁸ Research has identified 31 adaptation planning-related trainings (2012–2017) and 43 meetings, workshops, and summits (1998–2017).⁸ The state-funded Alaska Climate Change Impact Mitigation Program provides funding for hazard mitigation planning, including climate-related hazards such as flooding, coastal erosion, and permafrost thaw.^{8,135}

Adaptation Planning in Alaska

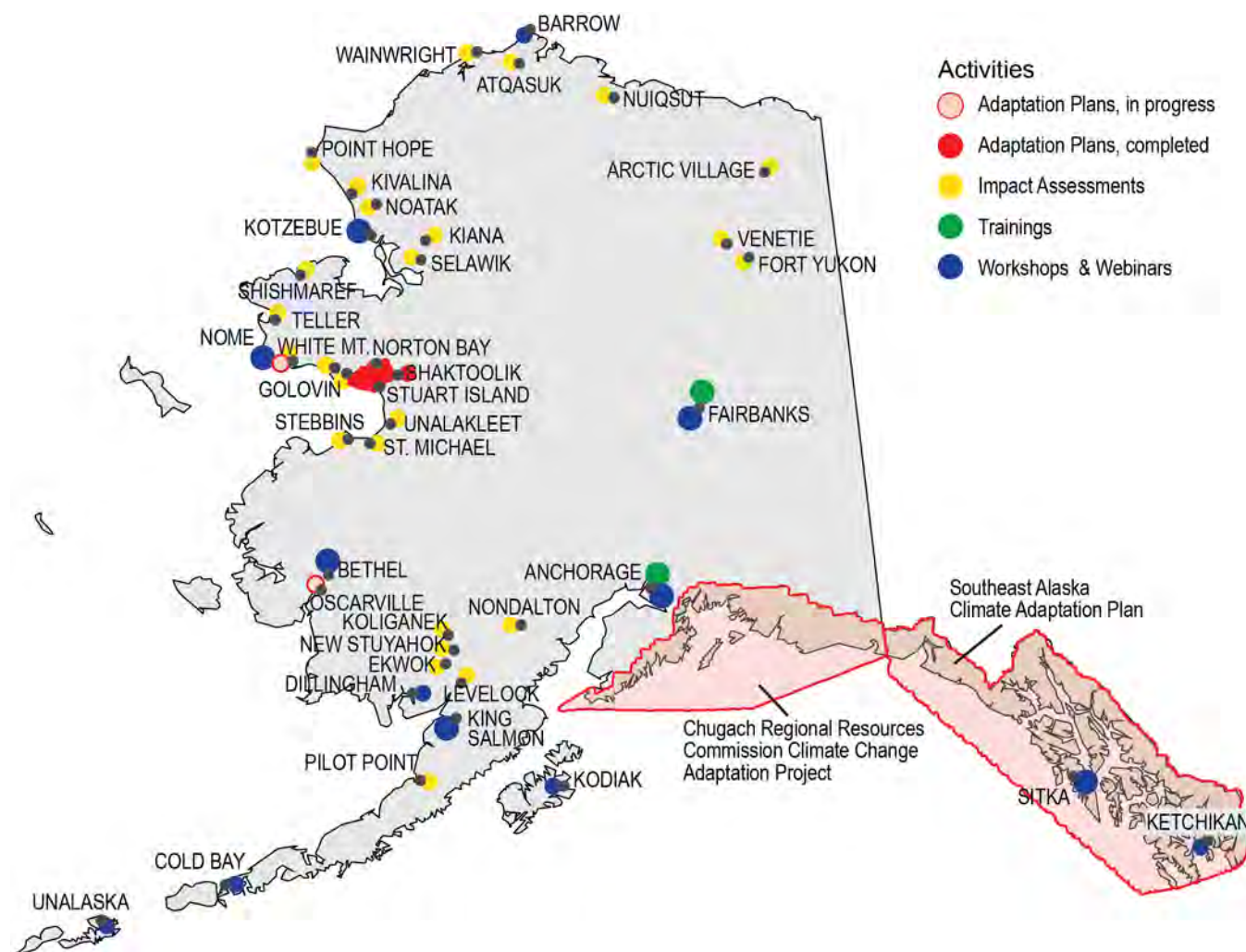


Figure 26.9: The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.^{1,2} Alaska is scientifically data poor, compared to other Arctic regions.³ In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;⁴ the University of Alaska for invasive species;⁵ and the Alaska Native Tribal Health Consortium for local observations of environmental change.⁶ Additional examples of community-based monitoring can be found through the website of the [Alaska Ocean Observing System](#).⁷ Source: adapted from Meeker and Kettle 2017.⁸

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

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

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

Examples of decision support tools in the state include the Historical Sea Ice Atlas and the SNAP (Scenarios Network for Alaska + Arctic Planning) climate-outlook community charts²⁷⁶ of projected temperature and precipitation for each community in Alaska. Periodically evaluating decision support tools helps to ensure their usefulness to stakeholders in practical decision contexts.²⁷⁷

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

A range of climate adaptation guidebooks exist that focus on climate adaptation planning in Alaska and neighboring Canada, which faces related adaptation challenges.¹³⁴ These guidebooks have been created by universities, governments, and nongovernmental organizations for a range of audiences, including rural Native Alaska communities, local governments, and state governments. Consistent across the

majority of the guidebooks are key phases in the adaptation planning process that include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities (Ch. 28: Adaptation).¹³⁴

Acknowledgments

Technical Contributors

Todd Brinkman

University of Alaska Fairbanks

Patricia Cochran

Alaska Native Science Commission

Jeff Hetrick

Alutiiq Pride Shellfish Hatchery

Nathan Kettle

University of Alaska Fairbanks

Robert Rabin

National Oceanic and Atmospheric Administration

Jacquelyn (Jaci) Overbeck

Alaska Department of Natural Resources

Bruce Richmond

U.S. Geological Survey

Ann Gibbs

U.S. Geological Survey

David K. Swanson

National Park Service

Todd Attwood

U.S. Geological Survey

Tony Fischbach

U.S. Geological Survey

Torre Jorgenson

Arctic Long Term Ecological Research

Neal Pastick
U.S. Geological Survey

Ryan Toohey
U.S. Geological Survey

Shad O'Neel
U.S. Geological Survey

Eran Hood
University of Alaska Southeast

Anthony Arendt
University of Washington

David Hill
Oregon State University

Lyman Thorsteinson
U.S. Geological Survey

Franz Mueter
University of Alaska Fairbanks

Jeremy Mathis
National Oceanic and Atmospheric Administration

Jessica N. Cross
National Oceanic and Atmospheric Administration

Jennifer Schmidt
University of Alaska Anchorage

David Driscoll
University of Virginia

Don Lemmen
Natural Resources Canada

Philip Loring
University of Saskatoon

Benjamin Preston
RAND Corporation

Stefan Tangen
University of Alaska Fairbanks

John Pearce
U.S. Geological Survey

Darcy Dugan
Alaska Ocean Observing System

Anne Hollowed
National Oceanic and Atmospheric Administration

USGCRP Coordinators
Fredric Lipschultz
Senior Scientist and Regional Coordinator

Susan Aragon-Long
Senior Scientist

Opening Image Credit
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Traceable Accounts

Process Description

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

Key Message 1

Marine Ecosystems

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

Description of evidence base

Changes in arctic sea ice and its impacts on marine ecosystems and various biological resources are well documented by 38 years of satellite records²⁸⁰ and the scientific literature.^{48,50,51,77,78,79,281} The finding of a continuing retreat of arctic sea ice is supported by sea ice modeling and continued CO₂ emissions.^{37,46} The northward distribution of ocean fish species is documented by numerous scientific papers: see Perry et al. (2005),²⁸² Thorsteinson and Love (2016),¹⁷ and Mecklenburg et al (2002).⁷² The impacts of an increased open Arctic sea contributing to increases in ocean acidification¹⁸ and expanding deeper into the Arctic Basin⁵⁷ will need validation with further studies.

Major uncertainties

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

Description of confidence and likelihood

There is *very high confidence* that the arctic sea ice will continue to reduce in size over the next 20–40 years, and it is *likely* that the Arctic Ocean will be nearly ice-free in late summer by mid-century based on current climate models. There is also *high confidence* that this melting will

have an effect on the northward expansion of North Pacific fish species and associated effects on associated food webs. There is *very high confidence* that continued melting of the Arctic Ocean ice will have an effect on the habitat and behavior of polar bear and walrus. There is *high confidence* that Alaska's ocean waters are becoming increasingly acidic. Given this increase, it is *very likely* that there will be biological impacts, but it is uncertain which species will be affected and to what extent.

Key Message 2

Terrestrial Processes

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

Description of evidence base

Permafrost

Multiple studies of permafrost in Alaska have shown that the gradual warming of the ground¹⁰⁵ has resulted in the warming and thawing of permafrost over the past 30 years,^{79,104,106} and spatial modeling projects that near-surface permafrost will potentially disappear on up to a quarter of the landscape by the end of the 21st century.¹⁰⁸ The magnitude of these changes depends on climate and ground-ice conditions, where permafrost thaw generally results in drier upland habitat and wetter lowlands as tundra and forests are converted to lakes and bogs.^{106,283} These changes will undoubtedly result in a number of societal consequences, loss of wildlife habitat, damage to infrastructure (including buildings, airport runways, tank farms, and roads), ecosystem contamination, and increased maintenance costs.^{20,21,91,207,284,285}

Wildfire

It has been well documented that wildfires are a common occurrence in Alaska, especially the interior boreal areas, although they have also occurred in areas of arctic tundra,^{114,286} with some of the largest fire years (1–6 million acres) occurring between 2004 to 2016 since records began around 1950.¹¹⁴ Recent studies show that changes in wildfire across the Alaska landscape could be attributed to human activity.²⁸⁷ This has resulted in changes in boreal vegetation cover^{95,96} and tundra communities.²⁸⁶ The increased fire frequency of recent decades is expected to continue into the future, in spite of the change to less flammable deciduous vegetation, because of the accompanying change to warmer and drier conditions.⁹⁵ The ground is warmer under post-fire deciduous vegetation, and thus fires will enhance the thaw of permafrost that is already underway due to climatic warming.²⁸⁸

Coastal and River Erosion

The shoreline along Alaska's northern coast has eroded at some of the fastest rates in the Nation, putting local communities, oil fields, and coastal habitat at risk.¹⁹ Unlike the contiguous United States, Alaska is subject to glacial and periglacial processes that make permafrost and sea ice key controlling factors of coastal erosion and flooding. Thermal degradation of permafrost leads to

enhanced rates of erosion along permafrost-rich coastal shorelines¹⁹ and subsidence of already low-lying regions. Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of more shoreline in the future.¹⁹

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

Glacier Change

Airborne altimetry surveys of Alaska glaciers spanning the 1994–2013 interval and covering about 40% of the region's glacierized area¹³⁷ yield decadal timescale mass balance estimates for individual glaciers and a regional estimate.²⁹¹ Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,^{139,140,141,142} with substantial regional-scale reductions in glacier area, volume (up to 40%–60% loss), and number. Moreover, physically based runoff models suggest that runoff from glaciers accounts for almost 40% of the total freshwater discharge into the Gulf of Alaska.²⁹²

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

Major uncertainties

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

Description of confidence and likelihood

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

across Alaska because of differences in local climatic and geographic qualities of the area in question. There is *high confidence* and it is *likely* that the glaciers in Alaska will continue to diminish, especially those that are tidewater glaciers.

Key Message 3

Human Health

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

Description of evidence base

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

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

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 4

Indigenous Peoples

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

Description of evidence base

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

Major uncertainties

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

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

Description of confidence and likelihood

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

Key Message 5

Economic Costs

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

Description of evidence base

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

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

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

Major uncertainties

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

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

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

Description of confidence and likelihood

There is *high confidence* and it is very likely that future damage to infrastructure from thawing permafrost and coastal erosion will cost hundreds of millions of dollars annually to repair or replace. There is *high confidence* and it is *likely* that timely repair and maintenance of

infrastructure can reduce damages and avoid some of the added costs. There is *medium confidence* and it is *very likely* that these costs will be offset in part by savings from reduced space heating needs.

Key Message 6

Adaptation

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

Description of evidence base

Research investigating costs of adapting to projected climate changes in Alaska in the realms of public infrastructure and wildfire suppression indicates cost savings from adaptation.^{21,91} Rural Alaska communities have high reliance on subsistence food resources. Access to these resources, as well as their habitat and migration patterns, is impacted by several factors, including climate change. Adaptation is thus important for maintaining livelihood security in these communities.^{125,246,247,248} Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change²⁴⁹ and ocean acidification.²⁵⁰ Rural communities in Alaska share many climatic, cultural, and ecosystem properties with rural communities across the Arctic. Research in Canada has documented the social and economic opportunities from adaptation in Northern communities.^{244,245}

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

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

A number of climate adaptation guidebooks focus on Alaska and Canada, which have related adaptation challenges.¹³⁴ Universities, governments, and nongovernmental organizations produced these guidebooks for a range of audiences, including rural Alaska Native communities, local governments, and state governments. Key phases in the adaptation planning process that are consistent across the majority of the guidebooks include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and

an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities.¹³⁴ Guidebooks specific to Alaska Natives and Canadian Inuit and First Nations peoples emphasize the importance of community support and participation in the adaptation planning process.¹³⁴

Major uncertainties

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

Description of confidence and likelihood

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

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

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Hawai'i and U.S.-Affiliated Pacific Islands

Federal Coordinating Lead Author**David Helweg**DOI Pacific Islands Climate Adaptation
Science Center**Chapter Lead****Victoria Keener**

East-West Center

Chapter Authors**Susan Asam**

ICF

Zena Grecni

East-West Center

Seema Balwani

National Oceanic and Atmospheric Administration

Malia Nobrega-Olivera

University of Hawai'i at Mānoa

Maxine Burkett

University of Hawai'i at Mānoa

Jeffrey Polovina

NOAA Pacific Islands Fisheries Science Center

Charles Fletcher

University of Hawai'i at Mānoa

Gordon Tribble

USGS Pacific Island Ecosystems Research Center

Thomas Giambelluca

University of Hawai'i at Mānoa

Review Editor**Jo-Ann Leong**

Hawai'i Institute of Marine Biology

Technical Contributors are listed at the end of the chapter.

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Hawai'i and U.S.-Affiliated Pacific Islands



Honolulu, Hawai'i

Key Message 1

Threats to Water Supplies

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

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

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

Key Message 3

Coastal Communities and Systems

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

Key Message 4

Oceans and Marine Resources

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

Key Message 5

Indigenous Communities and Knowledge

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

Key Message 6

Cumulative Impacts and Adaptation

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

Executive Summary



The U.S. Pacific Islands are culturally and environmentally diverse, treasured by the 1.9 million people who call

them home. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts.

A prevalent cause of year-to-year changes in climate patterns around the globe¹ and in the Pacific Islands region² is the El Niño–Southern Oscillation (ENSO). The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds. It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both

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

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

The impacts of sea level rise in the Pacific include coastal erosion,^{7,8} episodic flooding,^{9,10} permanent inundation,¹¹ heightened exposure to marine hazards,¹² and saltwater intrusion to surface water and groundwater systems.^{13,14} Sea level rise will disproportionately affect the tropical Pacific¹⁵ and potentially exceed the global average.^{16,17}

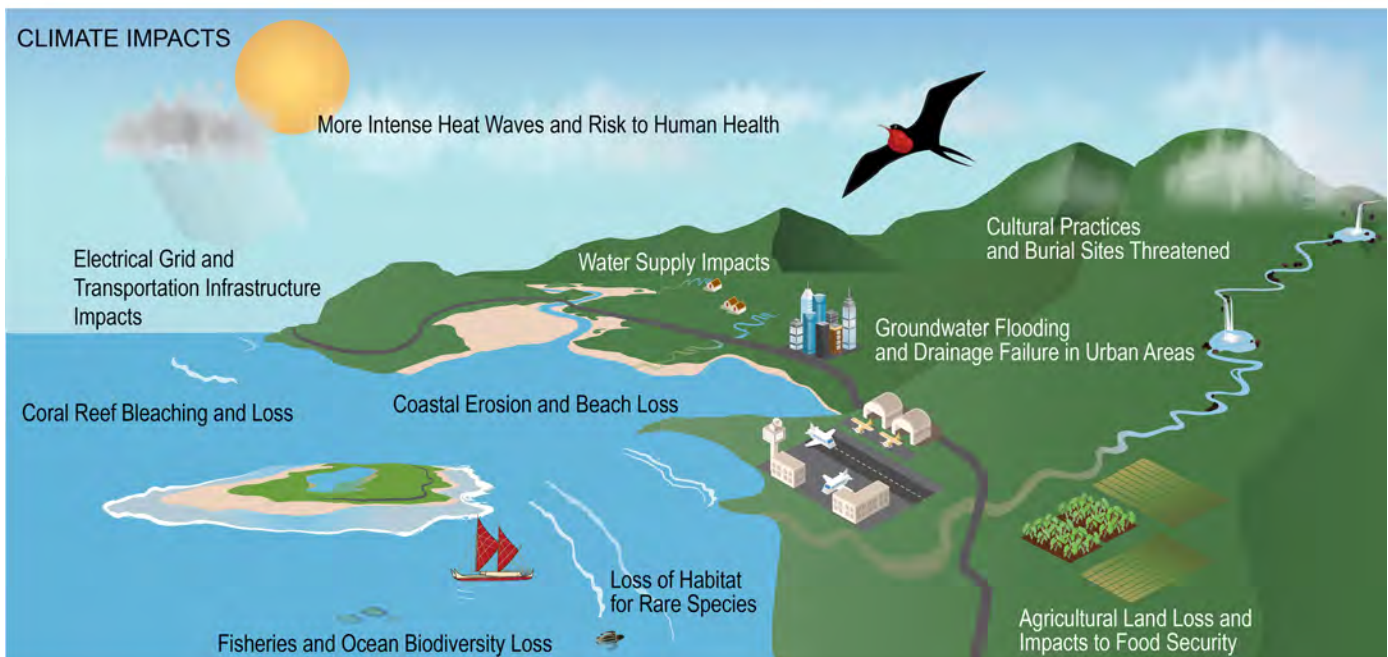
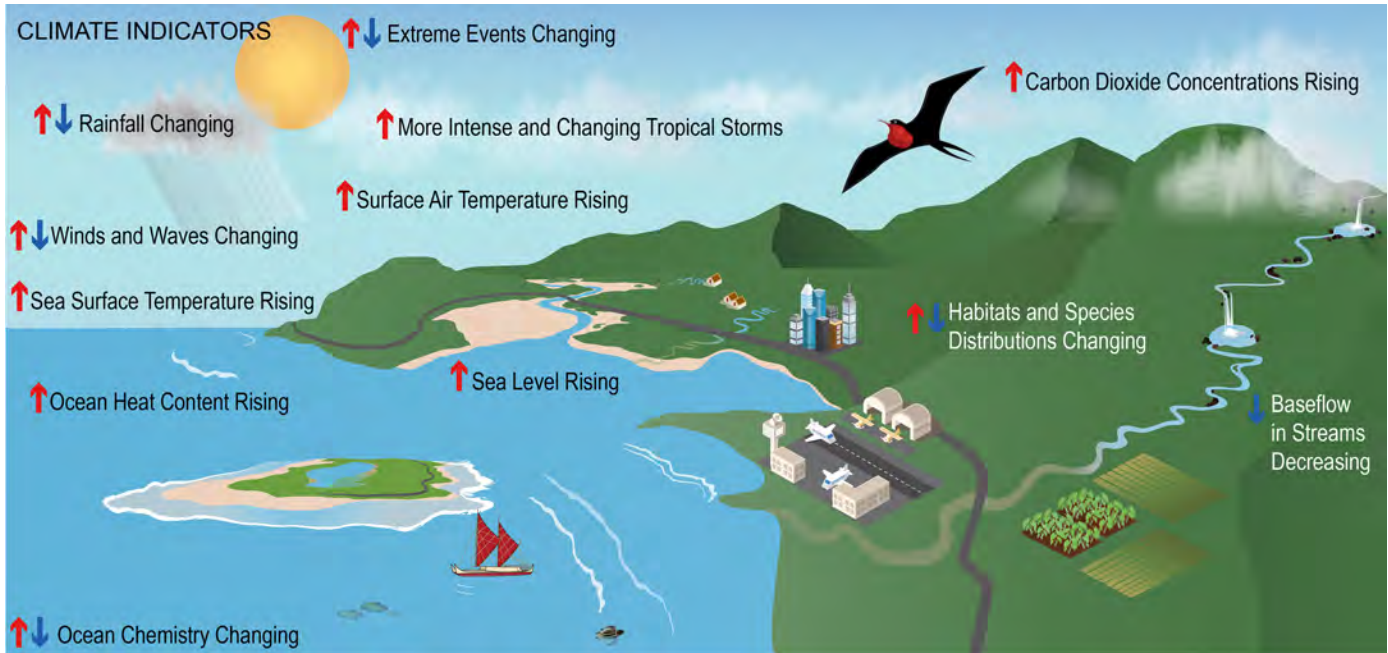
Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function. Inundation of atolls in the coming decades is projected to impact existing on-island ecosystems.¹⁸ Wildlife that relies on coastal habitats will likely also be severely impacted. In Hawai'i, coral reefs contribute an estimated \$477 million to the local economy every year.¹⁹ Under projected warming of

approximately 0.5°F per decade, all nearshore coral reefs in the Hawai'i and Pacific Islands region will experience annual bleaching before 2050. An ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.²⁰

Indigenous communities of the Pacific derive their sense of identity from the islands. Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands. The rich body of traditional knowledge is place-based and localized²¹ and is useful in adaptation planning because it builds on intergenerational sharing of observations.²² Documenting the kinds of governance structures or decision-making hierarchies created for management of these lands and waters is also important as a learning tool that can be shared with other island communities.

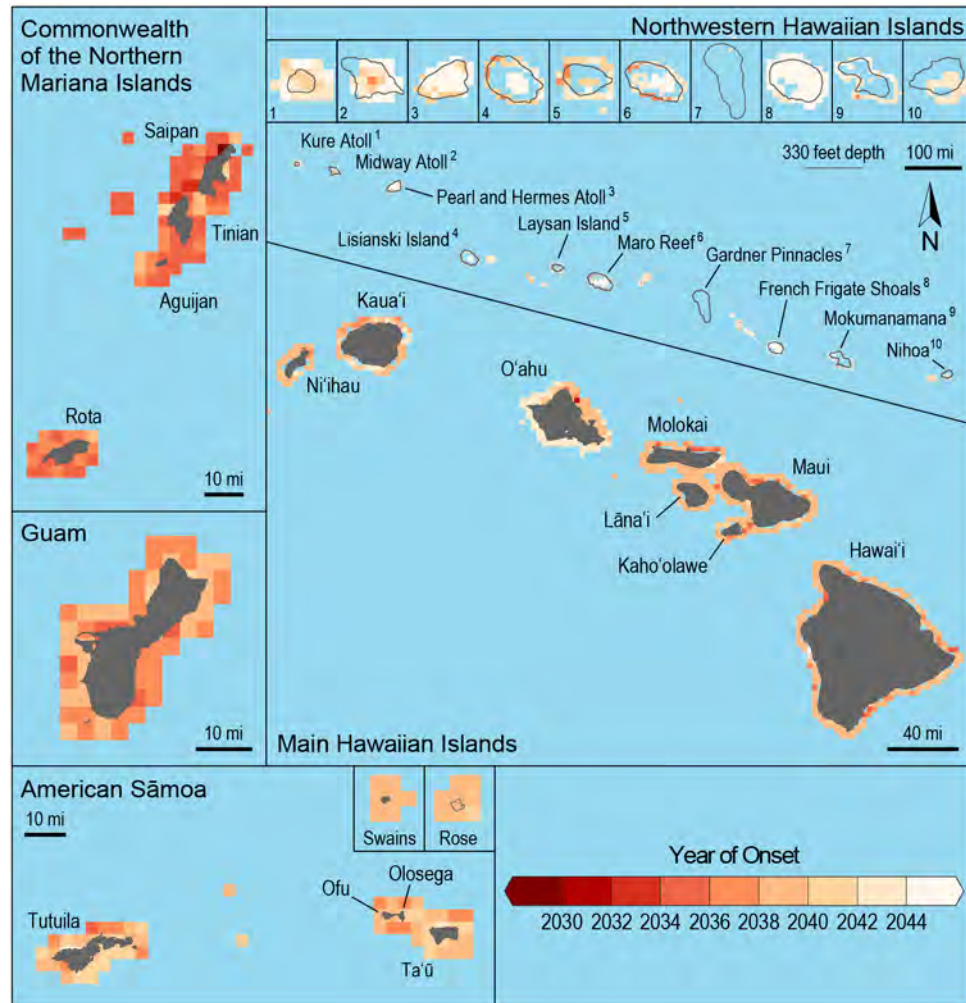
Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation as well as other climate-related impacts. Social cohesion is already strong in many communities, making it possible to work together to take action. Early intervention can lower economic,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

Climate Indicators and Impacts



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

Projected Onset of Annual Severe Coral Reef Bleaching



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

Background

The U.S. Pacific Islands (Figure 27.1) are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. The region comprises a vast ocean territory and more than 2,000 islands that vary in elevation, from high volcanic islands such as Mauna Kea on Hawai'i Island (13,796 feet) to much lower islands and atolls such as Majuro Atoll in the Republic of the Marshall Islands (the highest point on Majuro is estimated at 9 feet).^{24,25,26} Its environments span

the deepest point in the ocean (Mariana Trench National Monument) to the alpine summits of Hawai'i Island.²³ The region supports globally important marine and terrestrial biodiversity, as well as stunning cultural diversity (over 20 Indigenous languages are spoken).²³

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

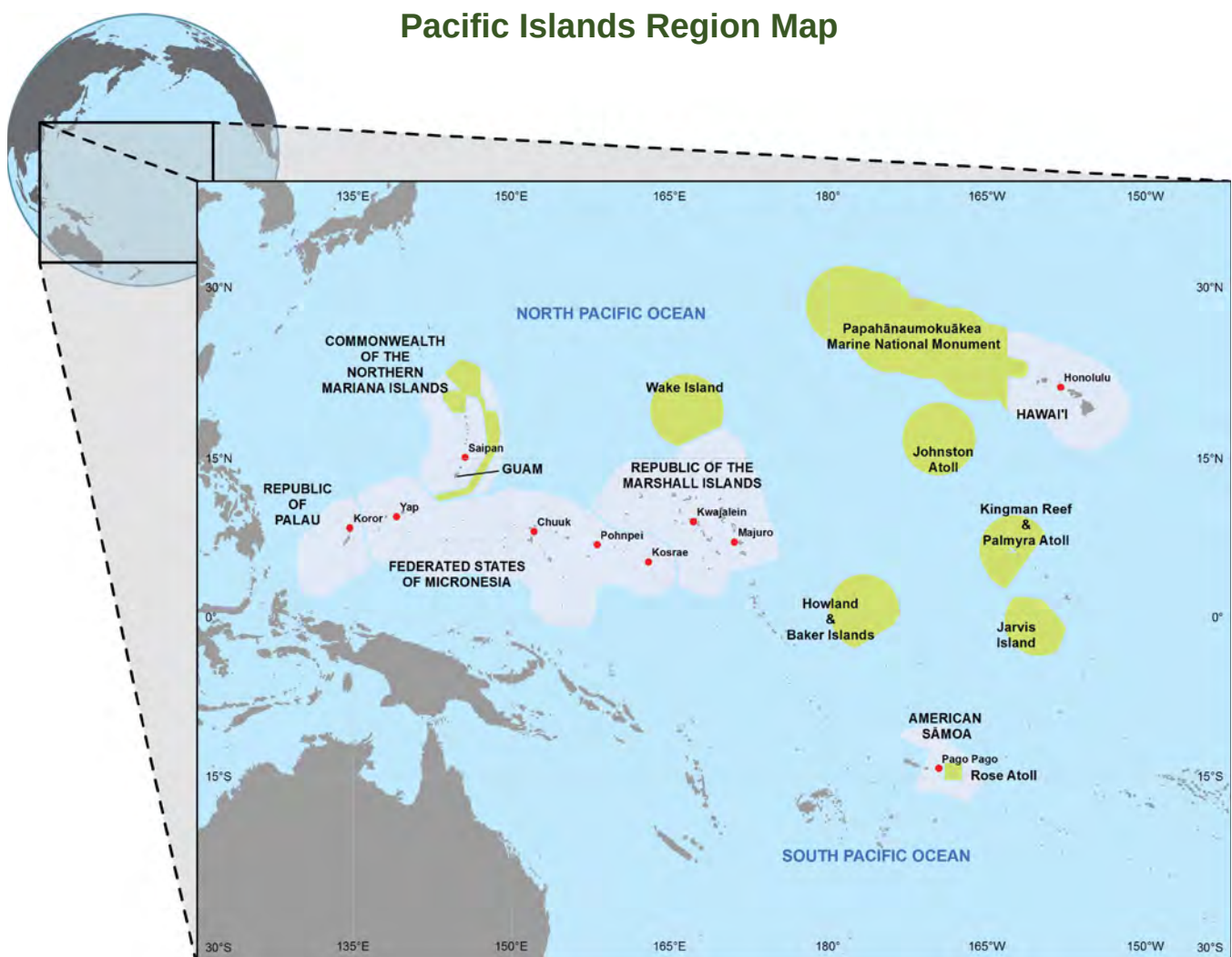


Figure 27.1: The U.S. Pacific Islands region includes the state of Hawai'i, as well as the U.S.-Affiliated Pacific Islands (USAPI): the Territories of Guam and American Sāmoa (AS), the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). While citizens of Guam and the CNMI are U.S. citizens, those from AS are U.S. nationals. Under the Compact of Free Association (COFA), citizens from FSM, RP, and RMI can live and work in the United States without visas, and the U.S. armed forces are permitted to operate in COFA areas. On this map, shaded areas indicate the exclusive economic zone of each island, including regional marine national monuments (in green). Source: adapted from Keener et al. 2012.²³

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

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

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

New Research Validates and Expands on Previous Assessment Findings

In previous regional climate assessments, key findings focused on describing observed trends and projected changes in climate indicator variables for specific sectors.^{23,32} In many cases, new observations and projections indicate that there is less time than previously thought for decision-makers to prepare for climate impacts.

Regionally, air and sea surface temperatures continue to increase, sea level continues to rise, the ocean is acidifying, and extremes such as drought and flooding continue to affect the islands.³³ New regional findings include (Figure 27.2)

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

Climate Indicators and Impacts

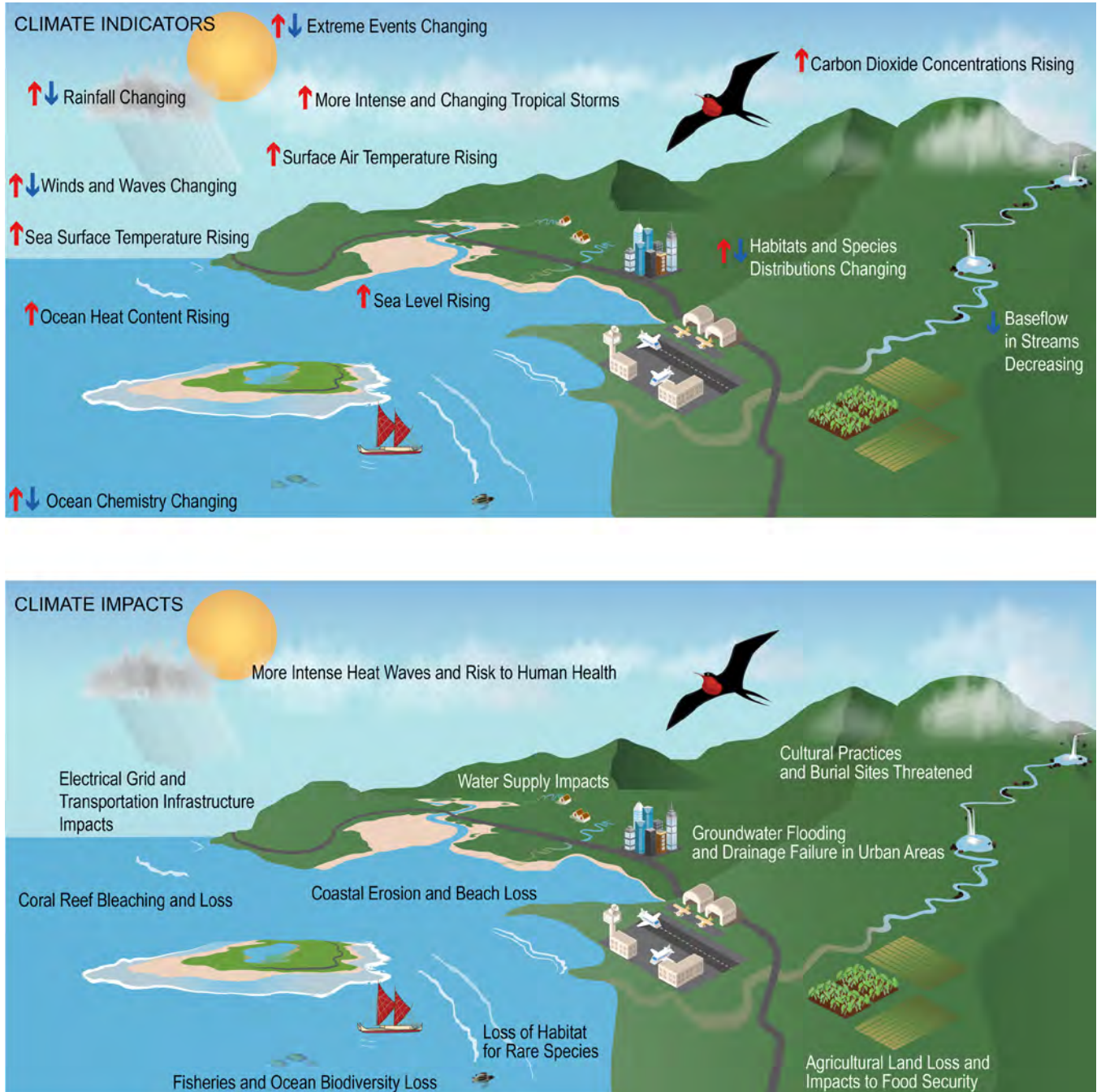


Figure 27.2: Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the Hawai'i and U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. Source: adapted from Keener et al. 2012.²³

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

The El Niño–Southern Oscillation (ENSO) phenomenon is a prevalent cause of year-to-year changes in climate patterns globally¹ and in the Pacific Islands region.² The effects of ENSO can be magnified when it is in phase with longer periodic cycles such as the Pacific Decadal Oscillation and the Interdecadal Pacific Oscillation.⁴⁹ The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds (for details about the different patterns of global climate variability, see Perlwitz et al. 2017).¹

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

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

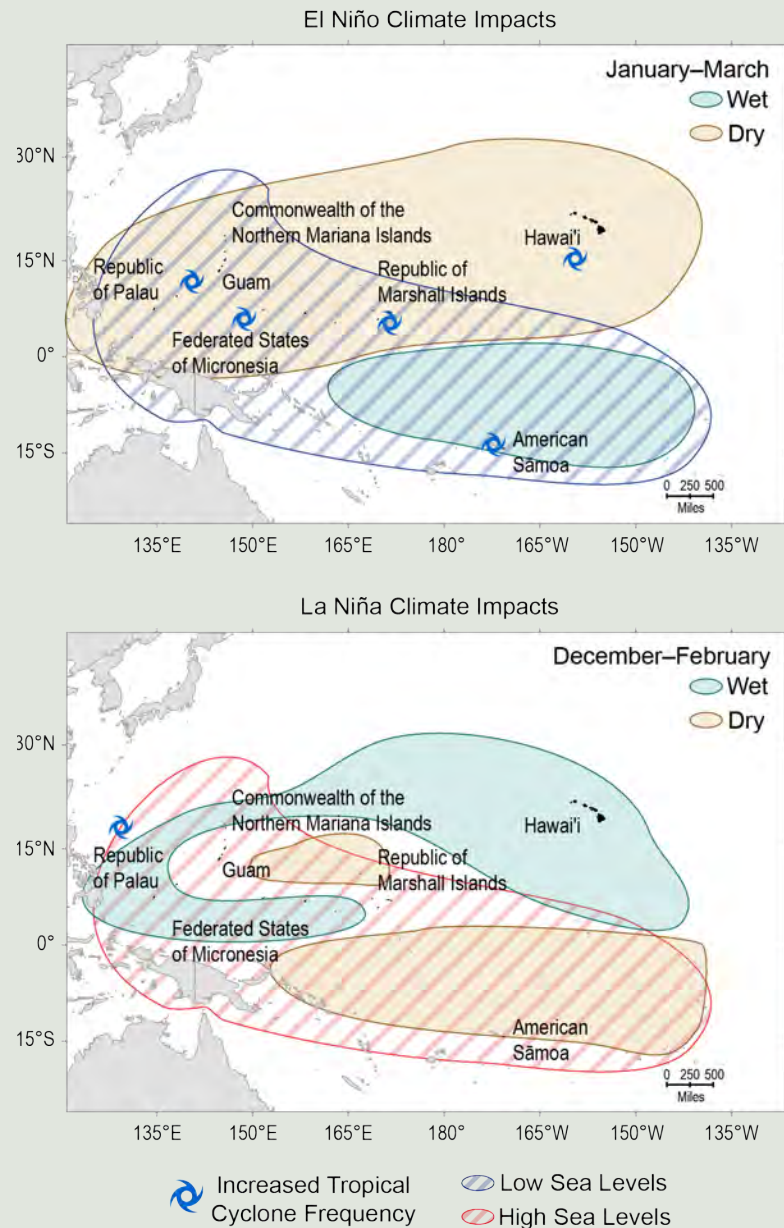


Figure 27.3: A prevalent cause of year-to-year changes in climate patterns in the U.S. Pacific Islands region is the El Niño–Southern Oscillation (ENSO) phenomenon. These maps show how (top) El Niño and (bottom) La Niña most commonly affect precipitation, sea level, and storm frequency in the Pacific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

Risks and Adaptation Options Vary with Geography

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

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

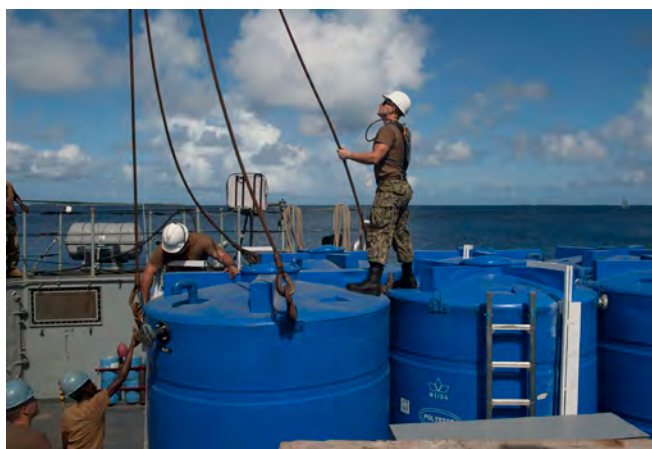
Key Message 1

Threats to Water Supplies

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

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

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



Emergency Drought Response Action for Island Residents

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

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

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

Climate shifts have already been observed in the region, with increases in temperature and

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

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

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

While rainfall in Hawai'i generally has been decreasing, it is also becoming more extreme.^{64,65} Both extreme heavy rainfall

events (causing increased runoff, erosion, and flooding) and droughts (causing water shortages) have become more common.⁶⁶ The number of consecutive wet days and

the number of consecutive dry days are both increasing in Hawai'i.⁶⁶ In American Sāmoa, drought magnitude and duration have minimal decreasing trends.²³

Hawai'i Annual Average Temperature Changes

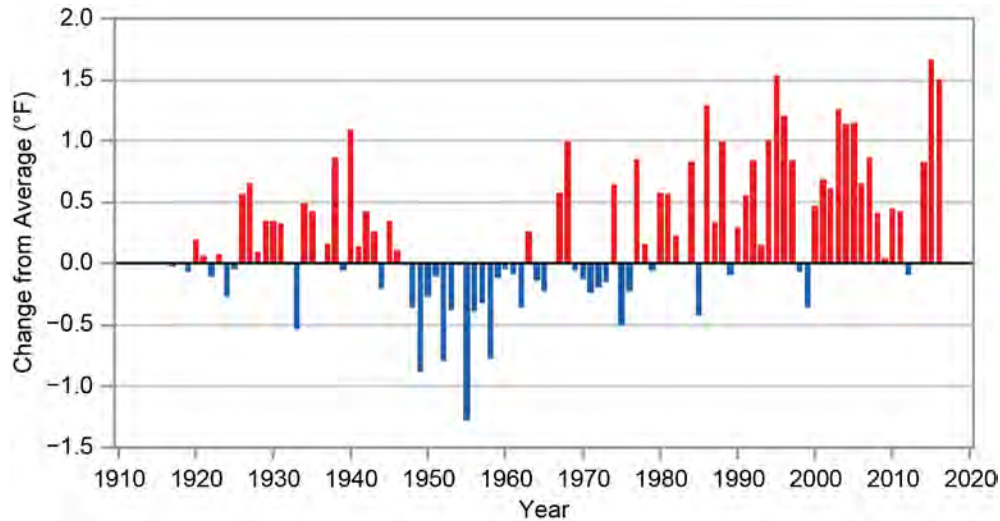


Figure 27.5: In Hawai'i, annual average temperatures over the past century show a statistically significant warming trend, although both warming and cooling periods occurred. Based on a representative network of weather stations throughout the islands, this figure shows the difference in annual average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

Hawai'i Rainfall Trends

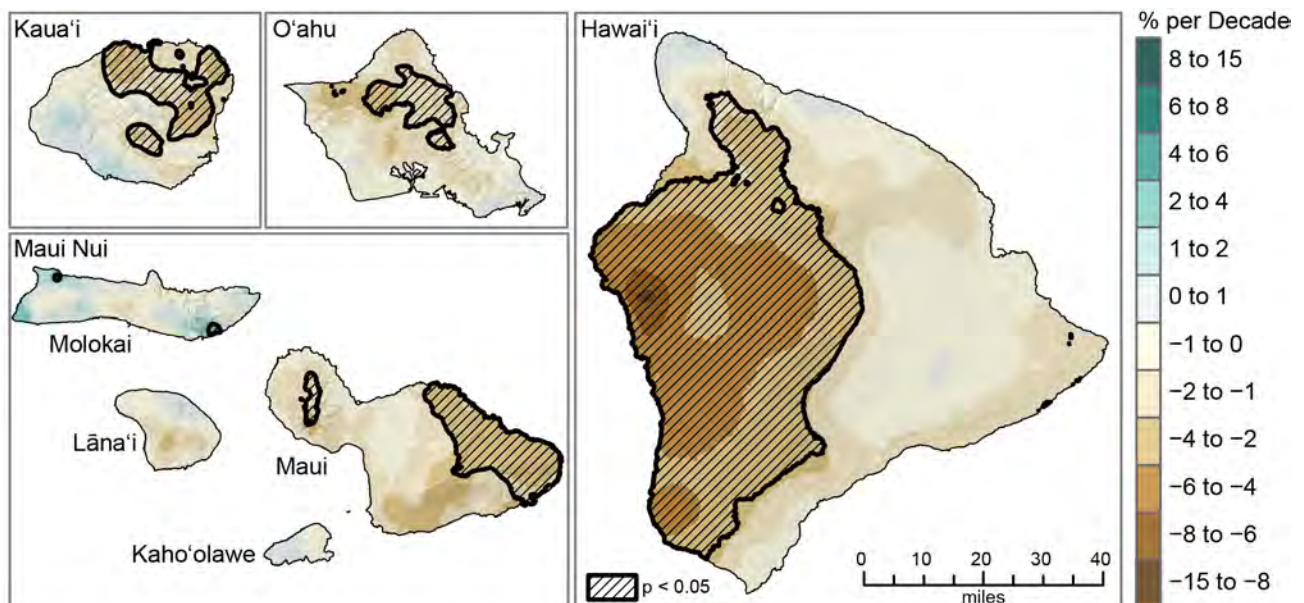


Figure 27.6: The figure shows the changes in annual rainfall (percent per decade) from 1920 to 2012 for the State of Hawai'i. Statistically significant trends are indicated with black hatching. Almost the entire state has seen rainfall decreases since 1920. The sharpest downward trends are found on the western part of Hawai'i Island. On other islands, significant decreases have occurred in the wetter areas. Source: adapted from Frazier & Giambelluca 2017.⁶⁰ © Royal Meteorological Society.

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

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

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

Adaptation. Impacts and risks from climate change will vary due to differences in hydrological characteristics and the governance

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

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

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

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

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

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

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

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

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

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

The Hawaiian Islands illustrate the challenges the broader Pacific region is facing. Ninety percent of the terrestrial species native to Hawai'i are endemic (unique to the region). New, and potentially invasive, species are arriving much more frequently than in the past.^{80,81} Hawai'i is home to 31% of the Nation's plants and animals listed as threatened or endangered, and less

than half of the landscape on the islands is still dominated by native plants.⁸² A similar picture describes most of the USAPI, as well. For example, Guam is well known for the decimation of its birds by the accidental introduction of the brown tree snake.

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

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

On many Pacific islands, native mangroves are highly productive coastal resources that provide a number of ecosystem services, including storm protection and food and building

materials for Indigenous and local communities. Mangroves also serve as fish nursery areas, trap land-based sediment that would otherwise flow to coral reefs,⁸⁵ and provide habitat for many species. They are important reservoirs of organic carbon, providing yet another ecosystem service.⁸⁶ Mangroves are already under threat from coastal development and logging. Climate change, particularly sea level rise, will likely add additional stress.^{87,88}

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

Throughout the Pacific, climate change will likely alter ecosystem services provided by agroforestry (the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits). In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, upland or inland forest services include substantial acreage in mixed agroforests (forests with

various trees, lower shrubs, and row crops used for food, building, and cultural practices).^{95,96} Agroforest production is impacted by drought, flooding, soil and water salinization (increased salt content in low-lying areas), wind, disease, pests, and clearing for development.⁷⁰ Climate change is projected to exacerbate these impacts in complex patterns related to the stressors present in specific locations.

Increases in air temperature are projected to have severe negative impacts on the range of Hawaiian

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

Hawaiian Forest Bird Species

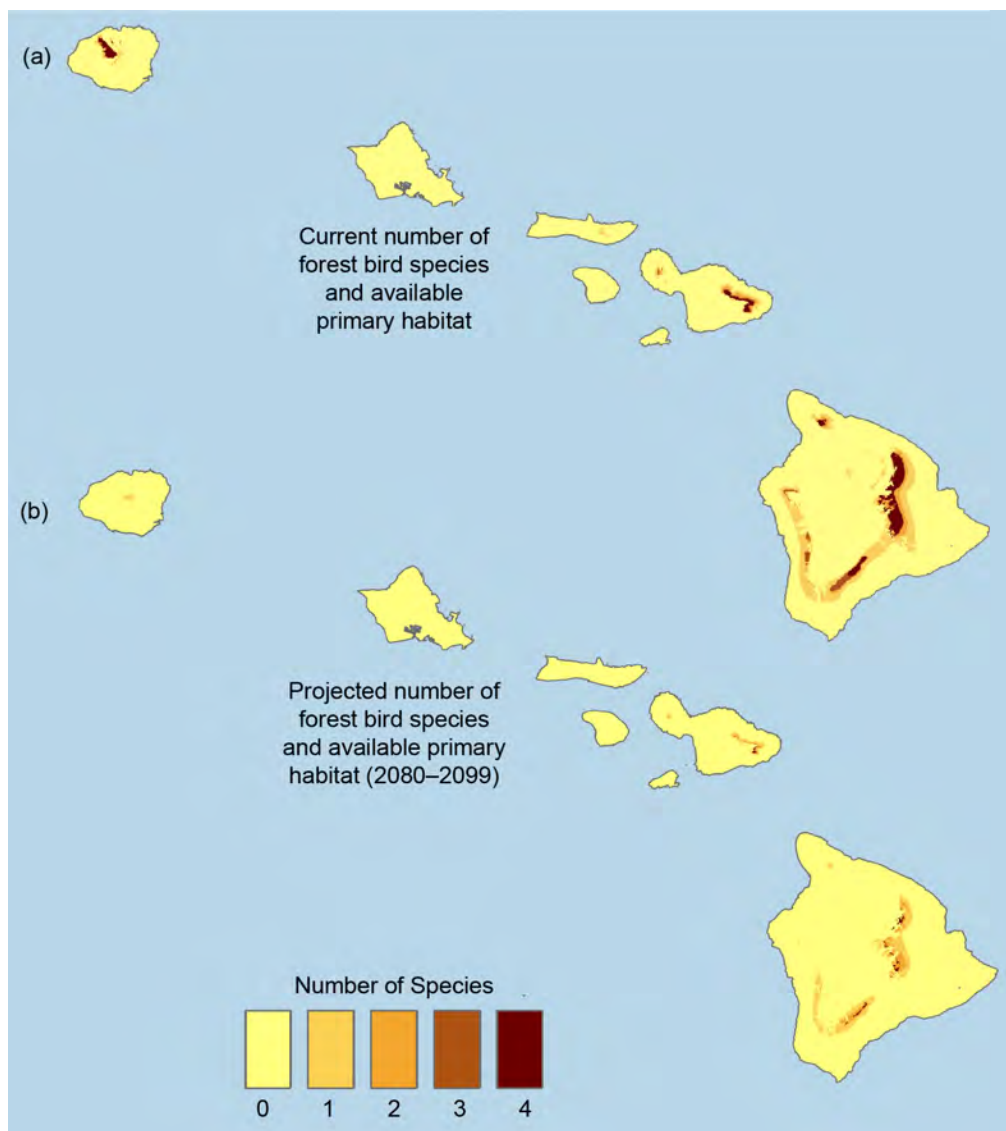


Figure 27.7: The figure shows the number of native Hawaiian forest bird species based on model results for (a) current and (b) future climate conditions. The future conditions are for the year 2100 using the middle-of-the-road scenario (SRES A1B). These projections include 10 species that represent the most rare and endangered native forest birds in Hawai'i. The number of these species and their available habitat are projected to be drastically reduced by 2100. Sources: adapted from Fortini et al. 2015⁴³ (CC BY 4.0).

Streams on U.S. Pacific Islands are also home to native fauna that are unique and typically restricted to specific island groups such as the Mariana, Sāmoan, and Hawaiian archipelagos. A model of streamflow and habitat on the Island of Maui suggests that physical habitat for stream animals will decrease by as much as 26% in some streams under a higher scenario (RCP8.5), but the overall forecast is for habitat changes of less than 5% by 2100.⁹⁸ Throughout Hawai'i, elevated stream water temperatures from urbanization and a warming climate will likely reduce available habitat for temperature-sensitive species. Additionally, the larvae of native Hawaiian stream animals develop in the ocean, and exposure to ocean acidification puts them at risk of physiochemical changes resulting in lower reproductive success.⁹⁹

Adaptation. Adapting to the impacts of climate change on terrestrial ecosystems is challenging. Management measures can take years to design and fund. Currently, understanding specific impacts of climate change on a particular ecosystem is confounded by other stressors (such as land development and invasive species) and clouded by a lack of precision in forecasting how sea level, rainfall, and air temperatures will change at the ecosystem or habitat level. A recent report summarizes both vulnerabilities and potential adaptations across all Hawaiian Islands and ecosystem types.¹⁰⁰ Through research and collaboration with Indigenous communities and land managers, ecosystem resilience to climate change can be enhanced and the most severe climate change effects on biodiversity decreased.¹⁰¹ Many Pacific island communities view the protection and management of native biodiversity as ways to reduce climate change impacts. For example, a watershed model of the windward side of Hawai'i Island suggested that control of an invasive tree with high water demand would partially offset decreases in streamflow that might be caused by a drier climate.⁴⁴ In

another example, resource managers are now keenly aware that climate change represents a serious long-term threat to Hawaiian forest birds. As a result, discussions involving multiple federal, state, and nongovernmental organization stakeholders are underway regarding a range of management responses, such as shifting protected areas, landscape-level control of avian malaria, and captive breeding and propagation. Some of these discussions are focused on adaptation to many aspects of climate change, whereas others address the broad range of threats to Hawaiian forest birds. Preparedness and planning can strengthen the resilience of native species and ecosystems to drought, wildfire, and storm damage, which will help them to avoid extinction due to climate change.

Key Message 3

Coastal Communities and Systems

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

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

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

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



Roadways Flood Periodically on O'ahu

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

Until recently, global sea level rise of about 3 feet by the end of the century was considered a worst-case scenario, becoming more likely without reductions in global greenhouse gas emissions.¹⁰⁶ However, new understanding about melting in Antarctica,^{107,108,109} Greenland,¹¹⁰ and alpine ice systems;¹¹¹ the rate of ocean heating;^{112,113} and historical sea level trends¹⁰³ indicates that it is physically possible to see more than double this amount this century (see Ch. 2: Climate, KM 4).^{17,114}

The Intermediate sea level rise scenario predicts up to 3.2 feet of global sea level rise by 2100; however, recent observations and

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

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

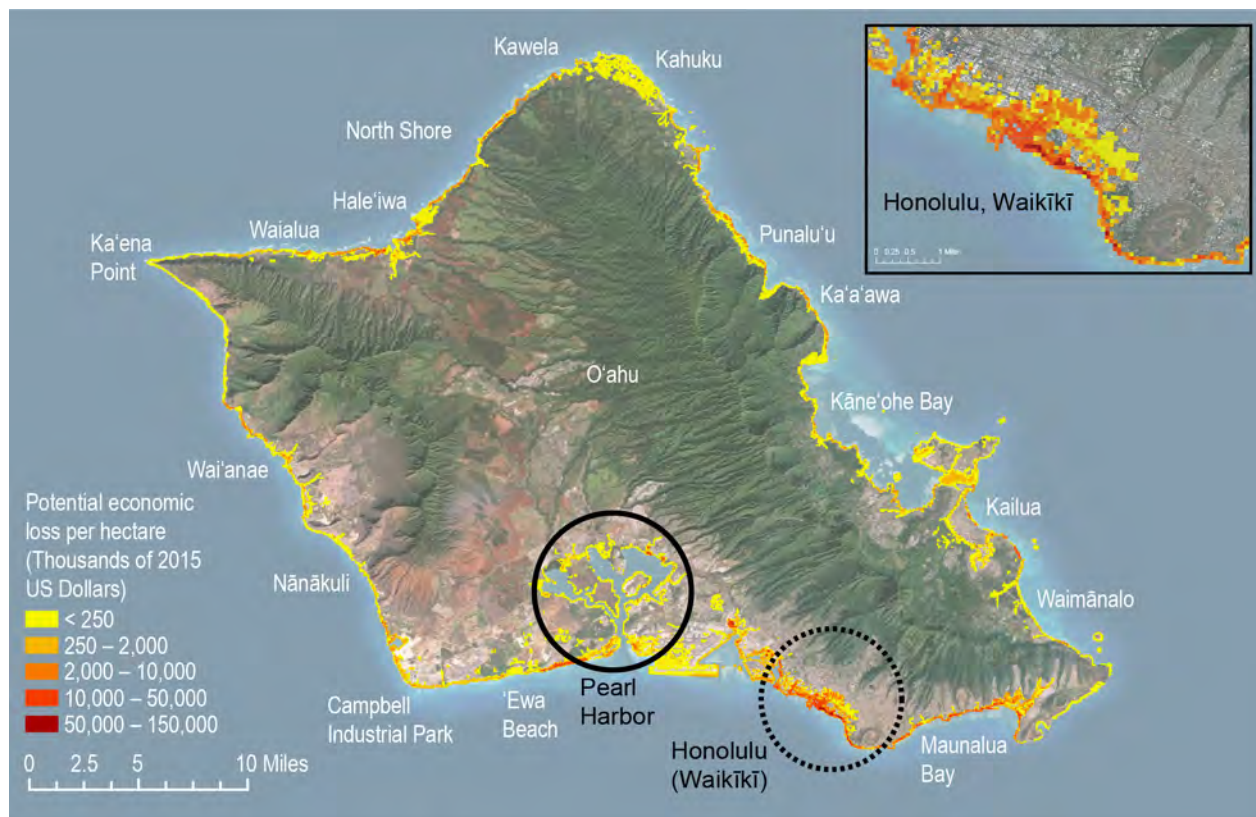


Figure 27.9: This map highlights potential economic losses (in 2015 dollars) in the exposure area associated with 3.2 feet of sea level rise on the island of O'ahu, Hawai'i. Potential economic losses are estimated from impacts to land and residential and commercial infrastructure. Highly impacted areas at risk of large economic losses include the U.S. Pacific Command and military infrastructure concentrated in Pearl Harbor (black circle) and the vulnerable tourist areas surrounding Waikiki (dashed black circle). Source: adapted by Tetra Tech Inc. from the Hawai'i Climate Change Mitigation and Adaptation Commission 2017.⁴²

Owing to global gravitational effects, sea level rise will disproportionately affect the tropical Pacific¹⁵ and potentially exceed the global average.¹⁶ This, plus sea level variability internal to the Pacific Basin (see Figure 27.3), means that parts of the region are likely to experience the highest rates of sea level rise on the planet.¹¹⁵ Scientific understanding of the timing and magnitude of future global sea level rise continues to improve,^{116,117} making regular updates of management plans and engineering codes an important activity for island communities.

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

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

In many areas, Pacific island coastal populations already exist on the edge of sustainability. Urban areas typically cluster around port facilities, as nearly all Pacific communities are

tied to goods and services delivered by cargo ships. As the world's most isolated chain of islands, Hawai'i imports nearly 90% of its food at a cost of more than \$3 billion per year (in 2004–2005 dollars),¹²⁰ resulting in government programs focused on food security.¹²¹ Without adaptation measures, the additional stress on sustainable practices related to sea level rise is likely to drive islanders to leave the region and make new homes in less threatened locations (see Key Message 6 and Case Study “Bridging Climate Science and Traditional Culture”).¹²²

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

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

Rising sea surface temperatures are shifting the location of fisheries (Ch. 9: Oceans, KM 2).¹²³ Ocean warming¹²⁴ and acidification,^{125,126} coupled with damaging watershed¹²⁷ and reef practices,¹²⁸ converge on island shores to increasingly limit the food resources that can be gathered from the sea (see Key Message 4).¹²⁹ Growing exposure to coastal hazards,

such as storm surges,¹³⁰ compounds this threat to sustainability.

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

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

There is great uncertainty about how Pacific variability occurring on shorter timescales (for example, El Niño and La Niña) will combine with multidecadal changes in temperature,

waves, rainfall, and other physical factors. This variability affects sea level extremes, which are likely to become more frequent this century,^{4,12} along with changes in precipitation,¹⁴⁰ ocean temperature,¹¹³ and winds.¹⁴¹ These, in turn, drive difficult-to-forecast stressors that challenge the sustainability of coastal communities.

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

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

Key Message 4

Oceans and Marine Resources

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

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

Climate change is already being observed in the Pacific Ocean. Sea surface temperatures and ocean pH, an indicator of acidity, are now beyond levels seen in the instrument record.¹⁵⁴ Additionally, oxygen levels in the subtropical Pacific have been declining over the past five decades, negatively impacting fishes that draw oxygen from the water.¹⁵⁵ Impacts from sea

level rise on coastal habitats and infrastructure have already occurred in the region, and the rate of sea level rise is projected to accelerate (see Key Message 3).

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

Under projected warming of approximately 0.5°F per decade, coral reefs will experience annual bleaching beginning in about 2035 in the Mariana Archipelago, in about 2040 in American Samoa and the Hawaiian Islands, and in about 2045 at other equatorial reefs (Figure 27.10).⁴⁶ Warming reductions on the order of the aims of the 2015 Paris Agreement are projected to delay the onset of annual severe bleaching by 11 years on average.⁴⁶ Because some coral species are more resilient to thermal stress than others, low levels of thermal stress are expected to only alter the types of corals present. However, at high levels of thermal stress, most coral species experience some bleaching and mortality.¹⁵⁸ Ocean acidification reduces the ability of corals to build and maintain reefs,^{125,159} while land-based nutrient input can substantially exacerbate acidification and reef erosion.¹⁶⁰ Under the higher scenario (RCP8.5), by the end of the century, virtually all coral reefs are projected to experience an ocean acidification level that will severely compromise their ability to grow.^{125,161} Loss of coral reef structure results in a decline in fish

abundance and biodiversity, negatively impacting tourism, fisheries, and coastal protection.¹²³ In the Hawaiian Archipelago under the higher scenario (RCP8.5), coral reef cover is projected to decline from the present level of 38% to 11% in 2050 and to less than 1% by the end of the century. This coral reef loss is projected to result in a total economic loss of \$1.3 billion per year in 2050 (in 2015 dollars, undiscounted) and \$1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, the lower scenario (RCP4.5) would avoid 16% of coral cover loss and \$470 million in damages per year (in 2015 dollars, undiscounted) compared to the higher scenario (RCP8.5).¹⁶² In the central and western Pacific, coral reef cover is projected to decline

by 2050 from a present-day average of 40% to 10%–20%, and coral reef fish production is expected to decline by 20% under a high emissions scenario (SRES A2).¹²³ Declines in maximum catch potential exceeding 50% from late-20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones (EEZs) of most islands in the central and western Pacific.¹⁶³ A key uncertainty is the extent to which corals can develop resilience to the rapidly changing ocean conditions.^{164,165} Changing ocean temperature and acidification will impact many other organisms that will likely alter the functioning of marine ecosystems.

Projected Onset of Annual Severe Coral Reef Bleaching

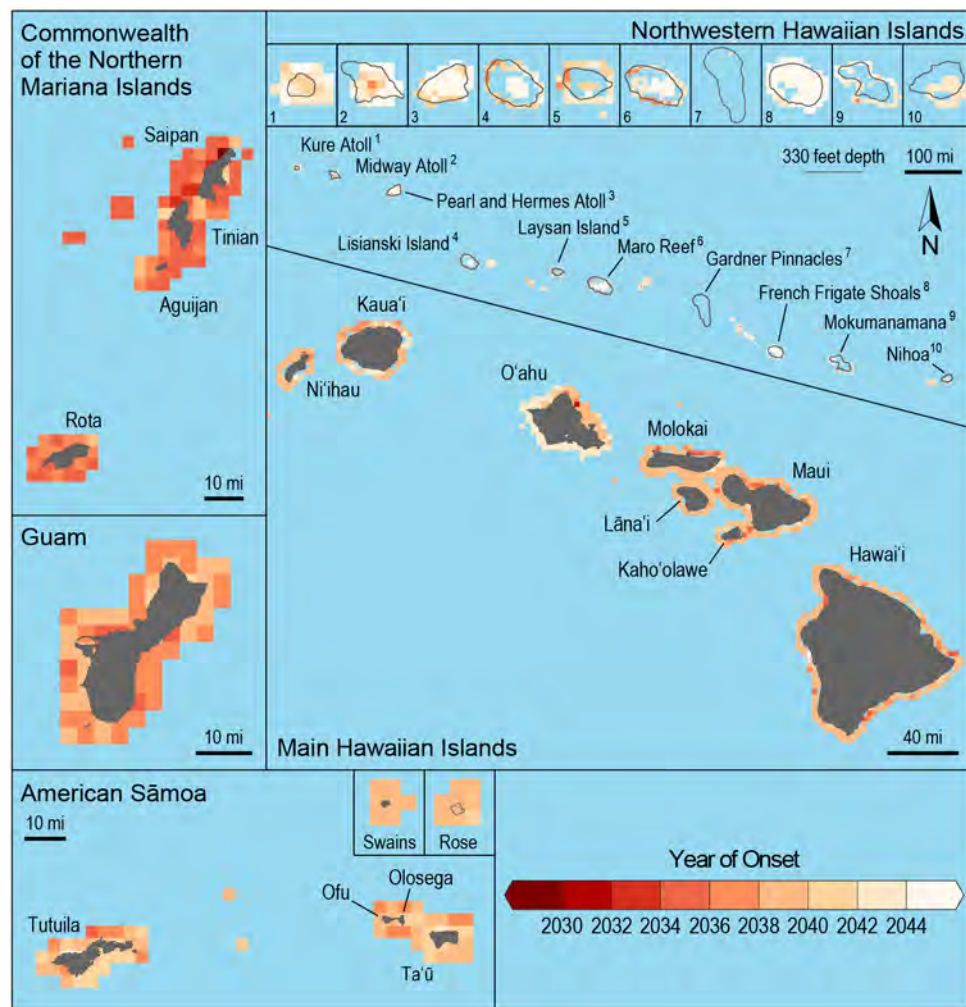


Figure 27.10: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai'i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F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

Mangroves provide coastal protection and nursery habitat for fishes and, in some cases, protect coral reefs from sediment and enhance the density of coral reef fishes.¹⁶⁶ Sea level rise has caused the loss of mangrove areas at sites in American Samoa⁸⁷ and is projected to further reduce mangrove area in the Pacific Islands region by 2100.^{87,88}

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

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

On low-lying islands and atolls, sea level rise is projected to result in the loss of resting and nesting habitat for sea birds and sea turtles and the loss of beach and pupping habitat for Hawaiian monk seals. Modeling exercises that take wave height into account project much greater habitat flooding than sea level rise alone would suggest.^{18,38,171} For example, sea level rise of about 6 feet combined with both

storm wave run-up and concurrent groundwater rise is projected to wash out 60% of the albatross nests across the U.S. Marine National Monuments each breeding season.⁸³

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

Key Message 5

Indigenous Communities and Knowledge

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

Indigenous communities of the Pacific have an inseparable connection to and derive their sense of identity from the lands, territories, and resources of their islands. This connection is traditionally documented in genealogical chants and stories transmitted through oral history.¹⁴⁶ The rich cultural heritage of Pacific island communities comprises spiritual, relational, and ancestral interconnectedness with the environment¹⁷⁴ and provides land security, water and energy security,

livelihood security, habitat security,¹⁷⁵ and cultural food security.¹⁷⁶ Climate change threatens this familial relationship with ancestral resources¹⁷⁷ and is disrupting the continuity that is required for the health and well-being of these communities (this experience is common to many tribal and Indigenous communities across the United States) (see Ch. 15: Tribes, KM 2).^{176,177}

Sea level rise imperils Indigenous communities of the Pacific. The sea that surrounds Pacific island communities continues to rise at a rate faster than the global average,¹¹⁵ with documented impacts on agriculture, coastal infrastructure, food security, livelihoods, and disaster management in the Republic of Palau¹⁴⁹ and the Republic of the Marshall Islands.¹⁴⁷

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



Salt Cultivation on Kaua'i

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

Case Study: Bridging Climate Science and Traditional Culture

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



Preparing Molokai's Fishponds for Climate Change

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

Ocean acidification and drought, in combination with pollution and development, are negatively affecting fisheries and ecosystems (which are drivers of tourism), directly impacting the livelihood security of Pacific communities. For example, across all Pacific island countries and territories, industrial tuna fisheries account

for half of all exports, 25,000 jobs, and 11% of economic production.¹⁷⁸ In Hawai'i, between 2011 and 2015, an annual average of 37,386 Native Hawaiians worked in tourism-intensive industries; based on the 2013 U.S. census, this number represents 12.5% of the Native Hawaiian population residing in Hawai'i.

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

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

rates of obesity and chronic diseases, such as diabetes, in the region.¹⁸²

The rich body of traditional knowledge is place-based and localized²¹ and is useful in adaptation because it builds on intergenerational sharing of observations²² of changes in climate-related weather patterns, ocean phenomena, and phenology (the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life). These observations, gathered over millennia, are useful in defining baselines and informing adaptive strategies.¹⁸³ Indigenous cultures are resilient, and their resilience has empowered Pacific island communities to survive several millennia on islands.¹⁸⁰ These communities have survived extreme events and responded to change through adaptive mechanisms based on traditional knowledge that has evolved over many generations.¹⁸⁴

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

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



Crop Trials of Salt-Tolerant Taro Varieties

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

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

Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced

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

Marshallese Traditional Agroforestry Calendar

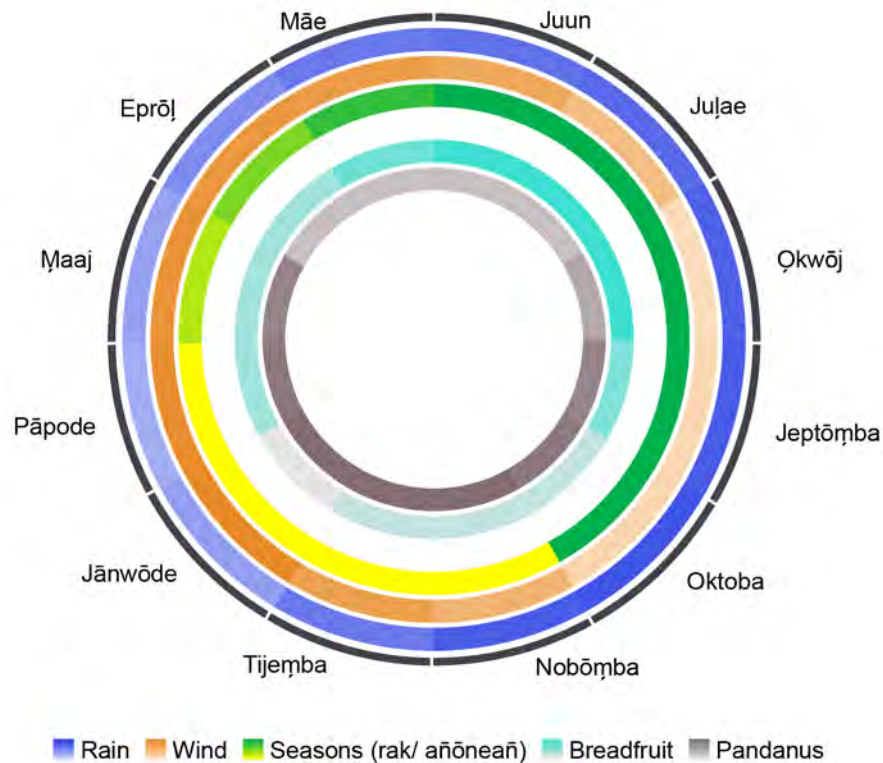


Figure 27.14: The Marshallese Traditional Agroforestry Calendar combines climate data and traditional season designations and knowledge about the harvest times of perennial crops throughout the year. Months are displayed in Marshallese on the outer ring, while inner rings show how wind and rain patterns and the harvest of two crops typically change throughout the year. The color gradients show the intensity of the harvest or the climate variable, with more intense colors representing larger amounts harvested or higher amounts of rain, for example, at various times. A web-based tool offers two versions, depending on the status of ENSO conditions. Source: adapted by Victor Garcia, Jr., from Friday et al. 2017.¹⁸⁸

Key Message 6

Cumulative Impacts and Adaptation

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

Sectoral impacts act together to compound environmental, social, cultural, and economic costs. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts. The interconnectedness of people in island communities and the interdependence between human activities and the natural environment¹¹⁹ mean that extreme events cause multiple, layered impacts, intensifying their effects (see Ch.17: Complex Systems). While each of these impacts presents challenges, when combined, the environmental, social, cultural, and economic impacts will have compounding costs. In addition, as some types of extreme events become more frequent, recovery from those events will prove increasingly difficult.

for isolated, resource-challenged islands,¹⁸⁹ resulting in long-term declines in people's welfare.^{190,191}

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

Sea level rise, the deterioration of coral reef and mangrove ecosystems (see Key Message 4), and the increased concentration of economic activity will make coastal areas more vulnerable to storms (see Key Message 3).¹⁹⁶ Pacific Islands already face underlying economic vulnerabilities and stresses caused

by unsustainable development, such as the use of beaches for building materials that results in coastal erosion or the waste disposal on mangroves and reefs that undermines critical ecological functions. The compounding impacts of climate change put the long-term habitability of coral atolls at risk, introducing issues of sovereignty, human and national security,¹⁹⁷ and equity,^{198,199,200} a subject of discussion at the international level.

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

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



Flooding in Kosrae

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



Reservoirs in the Marshall Islands

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



A Marshall Islands Storm

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

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

Climate change induced community relocation, a recognized adaptation measure, results in disruption to society–land relationships and loss of community identity.²¹⁴ Resettlement has resulted in people facing landlessness,

homelessness, unemployment, social marginalization, food insecurity, and increased levels of disease.¹²²

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

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

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

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

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

warning systems for typhoons, king tides, and coastal storms.

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

Social cohesion is already strong in many communities in the region, making it possible to work together to take action. Stakeholders representing academia, resource managers, and government came together across the State of Hawai'i to summarize ecosystem-specific vulnerabilities and prioritize potential

adaptations at the island scale.¹⁰⁰ In Molokai, a community-led effort is underway to prepare traditional fishponds for climate change (see Case Study “Bridging Climate Science and Traditional Culture”). One of the core benefits of this effort is the strengthening of relationships between the diverse people who will benefit from collaborating to address future climate change impacts on the island.

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

Acknowledgments

Technical Contributors

Malia Akutagawa

University of Hawai'i at Mānoa, Hawai'inuiākea School of Hawaiian Knowledge, Kamakakūokalani Center for Hawaiian Studies, William S. Richardson School of Law, Ka Huli Ao Center for Excellence in Native Hawaiian Law

Rosie Alegado

University of Hawai'i at Mānoa, Department of Oceanography, UH Sea Grant

Tiffany Anderson

University of Hawai'i at Mānoa, Geology and Geophysics

Patrick Barnard

U.S. Geological Survey–Santa Cruz

Rusty Brainard

NOAA Pacific Islands Fisheries Science Center

Laura Brewington

East-West Center, Pacific RISA

Jeff Burgett

Pacific Islands Climate Change Cooperative

Rashed Chowdhury

NOAA Pacific ENSO Applications Climate Center

Makena Coffman

University of Hawai'i at Mānoa, Urban and Regional Planning

Chris Conger

Sea Engineering, Inc.

Kitty Courtney

Tetra Tech, Inc.

Stanton Enomoto

Pacific Islands Climate Change Cooperative

Patricia Fifita

University of Hawai'i
Pacific Islands Climate Change Cooperative

Lucas Fortini

USGS Pacific Island Ecosystems Research Center

Abby Frazier

USDA Forest Service

Kathleen Stearns Friday

USDA Forest Service, Institute of Pacific Islands Forestry

Neal Fujii

State of Hawai'i Commission on Water Resource Management

Ruth Gates

University of Hawai'i at Mānoa, School of Ocean and Earth Science and Technology

Christian Giardina

USDA Forest Service, Institute of Pacific Islands Forestry

Scott Glenn

State of Hawai'i Department of Health, Office of Environmental Quality Control

Matt Gonser

University of Hawai'i Sea Grant

Jamie Gove

NOAA Pacific Islands Fisheries Science Center

Robbie Greene

CNMI Bureau of Environmental and Coastal Quality

Shellie Habel

University of Hawai'i at Mānoa, School of Ocean and Earth Science and Technology

Justin Hospital

NOAA Pacific Islands Fisheries Science Center

Darcy Hu

National Park Service

Jim Jacobi

U.S. Geological Survey

Krista Jaspers

East-West Center, Pacific RISA

Todd Jones

NOAA Pacific Islands Fisheries Science Center

Charles Ka'ai'ai

Western Pacific Regional Fishery Management Council

Lauren Kapono

NOAA Papahānaumokuākea Marine National Monument

Hi'ilei Kawelo

Paepae O He'eia

Benton Keali'i Pang

U.S. Fish and Wildlife Service

Karl Kim

University of Hawai'i, National Disaster Preparedness Training Center

Jeremy Kimura

State of Hawai'i Commission on Water Resource Management

Romina King

University of Guam and Pacific Islands Climate Adaptation Science Center

Randy Kosaki

National Oceanic and Atmospheric Administration

Michael Kruk

ERT, Inc.

Mark Lander

University of Guam, Water and Environmental Research Institute

Leah Laramée

State of Hawai'i Department of Land and Natural Resources

Noelani Lee

Ka Honua Momona

Sam Lemmo

State of Hawai'i Department of Land and Natural Resources, Interagency Climate Adaptation Committee

Rhonda Loh

Hawai'i Volcanoes National Park

Richard MacKenzie

USDA Forest Service, Institute of Pacific Islands Forestry

John Marra

National Oceanic and Atmospheric Administration

Xavier Matsutaro

Republic of Palau, Office of Climate Change

Marie McKenzie

Pacific Islands Climate Change Cooperative

Mark Merrifield

University of Hawai'i at Mānoa

Wendy Miles

Pacific Islands Climate Change Cooperative

Lenore Ohye

State of Hawai'i Commission on Water Resource Management

Kirsten Oleson

University of Hawai'i at Mānoa

Tom Oliver

University of Hawai'i at Mānoa, Joint Institute for Marine and Atmospheric Research

Tara Owens

University of Hawai'i Sea Grant

Jessica Podoski

U.S. Army Corps of Engineers—Fort Shafter

Dan Polhemus

U.S. Fish and Wildlife Service

Kalani Quiocho

NOAA Papahānaumokuākea Marine National Monument

Robert Richmond

University of Hawai'i, Kewalo Marine Lab

Joby Rohrer

O'ahu Army Natural Resources

Fatima Sauafea-Le'au

National Oceanic and Atmospheric Administration—American Sāmoa

Afsheen Siddiqi

State of Hawai'i Department of Land and Natural Resources

Irene Sprecher

State of Hawai'i, Department of Land and Natural Resources

Joshua Stanbro

City and County of Honolulu Office of Climate Change, Sustainability and Resiliency

Mark Stege

The Nature Conservancy—Majuro

Curt Storlazzi

U.S. Geological Survey—Santa Cruz

William V. Sweet

National Oceanic and Atmospheric Administration

Kelley Tagarino

University of Hawai'i Sea Grant

Jean Tanimoto

National Oceanic and Atmospheric Administration

Bill Thomas

NOAA Office for Coastal Management

Phil Thompson

University of Hawai'i at Mānoa, Oceanography

Mililani Trask

Indigenous Consultants, LLC

Barry Usagawa

Honolulu Board of Water Supply

Kees van der Geest

United Nations University, Institute for Environment and Human Security

Adam Vorsino

U.S. Fish and Wildlife Service

Richard Wallsgrove

Blue Planet Foundation

Matt Widlansky

University of Hawai'i, Sea Level Center

Phoebe Woodworth-Jefcoats

NOAA Pacific Islands Fisheries Science Center

Stephanie Yelenik

USGS Pacific Island Ecosystems Research Center

USGCRP Coordinators

Allyza Lustig

Program Coordinator

Fredric Lipschultz

Senior Scientist and Regional Coordinator

Opening Image Credit

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

Traceable Accounts

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

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

Key Message 1

Threats to Water Supplies

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

Description of evidence base

Vulnerability of water supplies to climate change: With their isolation and limited land areas, Hawai'i and the USAPI are vulnerable to the effects of climate change on water supplies.^{72,225} Ongoing and projected changes in temperature and precipitation will have negative effects on water

supplies in Hawai'i and some parts of the USAPI. For example, stream low flow and base flow in Hawai'i decreased significantly over the period 1913–2008, which is at least partly explained by a decline in precipitation.

Temperature change: In Hawai'i, air temperature increased by 0.76°F (0.42°C) over the past 100 years. The year 2015 was the warmest on record at 1.43°F (0.79°C) above the 100-year average. Mean and minimum (nighttime) temperatures both show long-term, statistically significant increasing trends, while the diurnal temperature range (the average difference between daily minimum and maximum temperature) shows a long-term, statistically significant decreasing trend.⁵⁹ Estimates of historical temperature changes in Hawai'i are based on the relatively few observing stations with long records and represent the best available data. Further temperature increases in the Hawai'i–USAPI region are highly likely. Northern tropical Pacific (including Micronesia) sea level air temperatures are expected to increase by 2.2°–2.7°F (1.2°–1.5°C) by mid-century and by 2.7°–5.9°F (1.5°–3.3°C) by 2100.⁶³ Southern tropical Pacific (including American Sāmoa) sea level air temperatures are expected to increase by 1.8°–3.1°F (1.0°–1.7°C) by mid-century and by 2.5°–5.8°F (1.4°–3.2°C) by 2100.⁶³ Increasing temperatures throughout the Hawai'i–USAPI region might cause increases in potential evapotranspiration,²²⁶ with consequent negative impacts on water supplies.

Precipitation change: While Hawai'i precipitation has experienced upward and downward changes across a range of timescales, more than 90% of the state had a net downward rainfall trend during 1920–2012.⁶⁰ Projections of future precipitation changes in Hawai'i are still uncertain. Using a dynamical downscaling approach to project climate changes in Hawai'i for the 20-year period at the end of the this century under a middle-of-the-road scenario (SRES A1B) resulted in increases in mean annual rainfall of up to 30% in the wet windward areas of Hawai'i and Maui Islands and decreases of 40% in some of the dry leeward and high-elevation interior areas.³⁴ Somewhat different results were obtained using an independent statistical downscaling method.³⁴ For the lower scenario (RCP4.5), mean annual rainfall in Hawai'i is projected by statistical downscaling to have only small changes in windward areas of Hawai'i and Maui Islands, to decrease by 10%–20% in windward areas of the other islands, and to decrease by up to 60% in leeward areas for the period 2041–2070. For the same scenario, the late-century (2071–2100) projection is similar to the 2041–2070 projection, except that a larger portion of the leeward areas will experience reductions of 20%–60%. For the higher scenario (RCP8.5), windward areas of Hawai'i and Maui Islands will see changes between +10% and –10%, and rainfall in leeward areas will decrease by 10% to more than 60% by the 2041–2070 period. By the late-century period (2071–2100), windward areas of Hawai'i and Maui Islands will see increases of up to 20%, windward areas on other islands will have decreases of 10% to 30%, and leeward areas will have decreases of 10% to more than 60%. The number of climate and water resources monitoring stations has declined across the region,^{23,76,77} reducing the ability of researchers to project future changes in climate.

Trends in hydrological extremes in Hawai'i: Increasing trends in extreme 30-day rainfall and the lengths of consecutive dry-day and consecutive wet-day periods⁶⁶ indicate that Hawai'i's rainfall is becoming more extreme and suggest that both droughts and floods are becoming more frequent in Hawai'i. With the addition of more years of observed data, and a more detailed spatiotemporal analysis from a grid-box level down to the island level, this contrasts with the earlier findings of a decreasing trend in the number of extreme rainfall events in Hawai'i.²²⁷

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

Major uncertainties

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

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

Description of confidence and likelihood

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

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

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

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

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

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

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

Description of evidence base

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

Forecasts of how climate change will affect rainfall and temperature in the main Hawaiian Islands have been based on both statistical and dynamical downscaling of global climate models (GCMs; see Traceable Account for Key Message 1). Statewide vulnerability models have been developed for nearly all species of native plants²³³ and forest birds,⁴³ showing substantial changes in the available habitat for many species. More detailed modeling within Hawai'i Volcanoes National Park has suggested that rare and listed plants being managed in Special Ecological Areas will experience climate changes that make the habitat in these areas unsuitable.⁹¹

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

Major uncertainties

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

Description of confidence and likelihood

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

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

Key Message 3

Coastal Communities and Systems

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

Description of evidence base

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

Changes in precipitation,²³⁵ Pacific sea level,⁴ climate variability,³ and the unsustainable practices of many human communities among Pacific islands¹²⁷ all converge to increase the vulnerability of coastal populations¹³⁵ as climate change continues in the future.⁵⁵ As sea level rises and average atmospheric temperature continues to increase, wave events³⁷ associated with changing weather patterns¹⁴⁰ constitute a growing mechanism for delivering¹² damaging saltwater into island aquifer systems,¹³ ecosystems,¹²⁹ and human infrastructure systems.¹⁷

In Hawai'i, studies by the Hawai'i Climate Change Mitigation and Adaptation Commission⁴² reveal that with 3.2 feet of sea level rise, over 25,800 acres of land in the state would be rendered unusable. Some of that land would erode into the ocean, some would become submerged by inches or feet of standing water, and some areas would be dry most of the year but repeatedly washed over by seasonal high waves. Statewide, about 34% of that potentially lost land is designated for urban use, 25% is designated for agricultural use, and 40% is designated for conservation. The loss of urban land is expected to increase pressure on the development of inland areas, including those designated as agricultural and conservation lands. Across the state, over 6,500 structures located near the shoreline would be compromised or lost with 3.2 feet of sea level rise. Some of these vulnerable structures include houses and apartment buildings, and their loss would result in over 20,000 displaced residents in need of new homes. The value of projected flooded structures, combined with the land value of the 25,800 acres projected to be flooded, amounts to over \$19 billion across the state (in 2013 dollars; \$19.6 billion in 2015 dollars). However, this figure does not encompass the full loss potential in the state, as monetary losses that would occur from the chronic flooding of roads, utilities, and other public infrastructure were not analyzed in this report and are expected to amount to as much as an order of magnitude greater than the potential economic losses from land and structures. For example, over 38 miles of major roads would be chronically flooded across the state with 3.2 feet of sea level rise. Utilities, such as water, wastewater, and electrical systems, often run parallel and underneath roadways, making lost road mileage a good indication of the extent of lost utilities. This chronic flooding of infrastructure would have significant impacts on local communities as well as reverberating effects around each island.

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

Marra and Kruk (2017)¹⁴² describe climate trends for the USAPI. Globally and locally, observations of GHG concentrations, surface air temperatures, sea level, sea surface temperature, and ocean acidification show rising trends at an increasing rate. Trends in measures of rainfall, surface

winds, and tropical cyclones are not as readily apparent. Patterns of climate variability characterize these measures and tend to mask long-term trends. A lack of high-quality, long-term observational records, particularly with respect to in situ stations, contributes to difficulties in discerning trends. To maintain and enhance our ability to assess environmental change, attention needs to be given to robust and sustained monitoring.

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 4

Oceans and Marine Resources

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

Description of evidence base

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

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

Ocean acidification: Atmospheric carbon dioxide levels recorded at Mauna Loa, Hawai'i, have recently exceeded 400 parts per million, and oceanic pH levels measured off O'ahu have steadily declined from an annual average of about 8.11 to 8.07 over the past 25 years (data from Hawai'i Ocean Time Series, SOEST, University of Hawai'i) and are projected to decrease to 7.8 by 2100.¹²³ As pH declines, it lowers the saturation level of aragonite (the form of calcium carbonate used by corals and many other marine organisms), reducing coral and shell growth.¹²⁵ By the end of the century, aragonite saturation is projected to decline from a current level of 3.9 to 2.4, representing extremely marginal conditions for coral reef growth.^{32,123,159,161}

Bleaching events: These continue to occur—most recently over successive years—with widespread impacts.^{45,158} Sea surface temperature time series from a suite of Climate Model Intercomparison Project 5 outputs that are statistically downscaled to 4 km resolution are used to project the year when coral reefs will begin to experience annual bleaching under the higher scenario (RCP8.5).⁴⁶ These data forecast that bleaching will be an annual event for the region starting in about 2035.⁴⁶

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

Coral reef ecosystem impacts: Coral reef cover around the Pacific Islands region is projected to decline from the current average level of about 40% to 15%–30% by 2035 and 10%–20% by 2050.¹²³ The loss of coral reef habitat is projected to reduce fish abundance and fisheries yields by 20%.¹²³ Loss of coral reefs will result in increased coastal erosion.^{23,236} Tourism is the major economic engine in Hawai'i, and healthy coral reef ecosystems are critical to this economy. Under the higher scenario (RCP8.5), coral reef loss is projected to result in a total economic loss of \$1.3 billion per

year in 2050 and \$1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, a lower scenario (RCP4.5) would avoid 16% of coral cover loss and \$470 million per year (in 2015 dollars, undiscounted) compared to the higher scenario.¹⁶² The confidence intervals around these loss estimates under RCP8.5 for 2050 range from a gain of \$240 million to a loss of \$1.9 billion, and for 2090 range from a loss of \$1.7 billion to \$1.9 billion (in 2015 dollars, undiscounted).¹⁶²

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

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

Major uncertainties

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

Description of confidence and likelihood

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

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

There is *high confidence* that bleaching and rising seawater acidity will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection. This is deemed *very likely* because significant coral mortality has recently been observed in western Hawaiian coral reefs that suffered from the 2015 bleaching event. Further, the positive relationship between fish

density and coral reef cover is well established. The magnitude of this impact depends on the extent that coral species exhibit adaptive or resilience capacity.

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

Key Message 5

Indigenous Communities and Knowledge

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

Description of evidence base

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

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

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

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

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

Major uncertainties

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

Description of confidence and likelihood

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

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

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

Key Message 6

Cumulative Impacts and Adaptation

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

Description of evidence base

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

The *Climate Science Special Report* (CSSR) summarizes extensive evidence that is documented in the climate science literature and is similar to statements made in NCA3 and international¹⁰⁶ assessments.³³ More recent downscaling studies have further supported these assessments,²⁴⁸ though pointing out that the changes (future increased intensity and TC precipitation rates) will not necessarily occur in all basins.²⁴⁶

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

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

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

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

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

The social science research on climate and conflict suggests a possible association between climate variability and change and conflict. Consensus or conclusive evidence of a causal link

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

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

Major uncertainties

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

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

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

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

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

The degree to which climate variability and change impact conflict, and related causal pathways, remains uncertain. This is compounded by the fact that different types of conflict—social, political,

civil, or violent—are conflated.^{209,251} Violent conflict can describe interpersonal-, intergroup-, and international-level disputes. Some researchers contend that systematic research on climate change and armed conflict has not revealed a direct connection.²⁵² Gemenne et al. (2014)²⁰⁸ argue that there is a lack of convincing empirical evidence or theories that explain the causal connection between climate change and security. They do, however, note that there is some evidence for statistical correlation between climatic changes and conflict, broadly referenced.

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

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

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

Description of confidence and likelihood

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

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

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

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Reducing Risks Through Adaptation Actions

Federal Coordinating Lead Authors**Jeffrey Arnold**

U.S. Army Corps of Engineers

Roger Pulwarty

National Oceanic and Atmospheric Administration

Review Editor**Mary Ann Lazarus**

Cameron MacAllister Group

Chapter Lead**Robert Lempert**

RAND Corporation

Chapter Authors**Kate Gordon**

Paulson Institute

Katherine Greig

Wharton Risk Management and Decision
Processes Center at University of Pennsylvania
(formerly New York City Mayor's Office of Recovery
and Resiliency)

Cat Hawkins Hoffman

National Park Service

Dale Sands

Village of Deer Park, Illinois

Caitlin Werrell

The Center for Climate and Security

Technical Contributors are listed at the end of the chapter.

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Reducing Risks Through Adaptation Actions



Key Message 1

Seawall surrounding Kivalina, Alaska

Adaptation Implementation Is Increasing

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

Key Message 2

Climate Change Outpaces Adaptation Planning

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

Key Message 3

Adaptation Entails Iterative Risk Management

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

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

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

Key Message 5

New Approaches Can Further Reduce Risk

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

Executive Summary

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

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

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

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

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

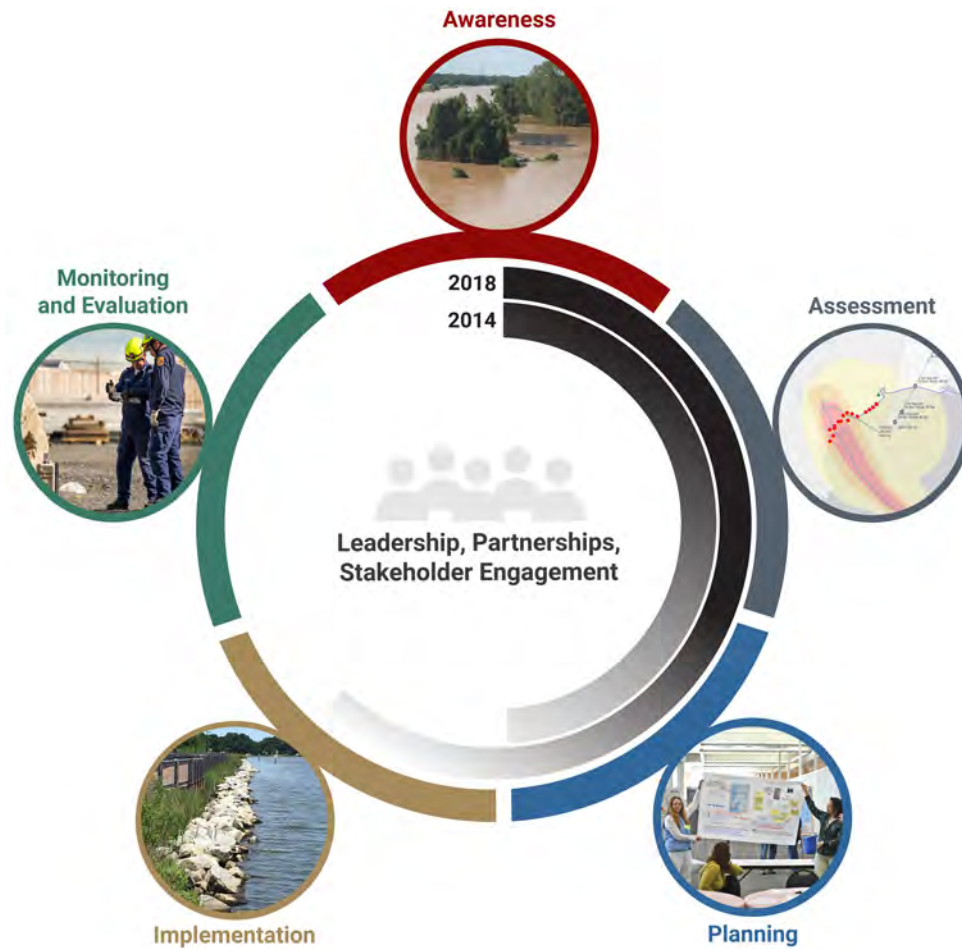
Achieving the benefits of adaptation can require up-front investments to achieve longer-term savings, engaging with differing stakeholder interests and values, and planning in the face of uncertainty. But adaptation also presents challenges, including difficulties in obtaining the necessary funds, insufficient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

In general, adaptation can generate significant benefits in excess of its costs. Benefit-cost analysis can help guide organizations toward

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

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

Five Adaptation Stages and Progress



The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. *From Figure 18.1 (Source: adapted from National Research Council, 2010.¹ Used with permission from the National Academies Press, ©2010, National Academy of Sciences).*

Introduction

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

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

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

Adaptation involves managing both short- and long-term risks. Many important climate-influenced effects—storm intensity, sea level, frequency of heat waves—have already changed due to past greenhouse gas (GHG) emissions and will continue to change in the decades ahead.^{3,4} Because several GHGs, in particular carbon dioxide, reside in the atmosphere for decades or longer, many climate-influenced effects are projected to continue changing

through 2050, even if GHG emissions were to stop immediately. Thus, climate risk management requires adaptation for the next several decades, independent of the extent of GHG emission reductions. After 2050, the magnitude of changes, and thus the demands on adaptation, begins to depend strongly on the scale of GHG emissions reduction today and over the coming decades.^{4,9}

Individuals, business entities, governments, and civil society as a whole can take adaptation actions at many different scales. Some of these are changes to business operations, adjustments to natural and cultural resource management strategies, targeted capital investments across diverse sectors, and changes to land use and other policies. Adaptation actions can yield beneficial short-term and/or longer-term outcomes in excess of their costs, based on economic returns, ecological benefits, and broader concepts of social welfare and security. Moreover, many strategies can provide multiple benefits, resulting in long-term cost savings. For example, restoring wetlands can provide valuable habitat for fish and wildlife as well as flood protection to nearby communities,¹⁰ and conserving mangrove ecosystems can protect coastal communities from damaging storms¹¹ as well as help to store carbon.¹²

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

Integrating climate risk management into existing design, planning, and operations

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

Key Message 1

Adaptation Implementation Is Increasing

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

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

Emergency Planning Agency and California Natural Resources Agency 2012¹⁹).

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

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

Five Adaptation Stages and Progress



Figure 28.1: The figure illustrates the adaptation iterative risk management process. The gray arced lines compare the current status of implementing this process with the status reported by the Third National Climate Assessment in 2014. Darker color indicates more activity. Source: adapted from National Research Council, 2010.¹ Used with permission from the National Academies Press, ©2010, National Academy of Sciences.

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

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

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

to exploit synergies among various types of actions, and many plans pay little attention to the costs of actions or their co-benefits. Often explicit attention to evaluation and monitoring is scant or nonexistent.

Managing the Challenge

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

Box 28.2: Adaptation Actions by Individuals

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

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

Key Message 2

Climate Change Outpaces Adaptation Planning

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

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

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

Adjusting to projected climate risk, rather than relying on interpretations of past impacts, has

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

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

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

of climate model projections produced with myriad uncertainties whose local implications may differ significantly across each projection.

Key Message 3

Adaptation Entails Iterative Risk Management

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

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

Iterative risk management emphasizes that the process of anticipating and responding to climate change does not constitute a single

set of judgments at any point in time; rather, it is an ongoing cycle of assessment, action, reassessment, learning, and response.⁴¹ The process helps manage risks that are well known, as well as those that are deeply uncertain due to data limitations or the irreducible unpredictability of some aspects of current and future climate.^{33,42}

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

Adaptation Actions to Reduce Risk

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

1. reduce exposure (for example, reduce the presence of people or assets in locations that could be adversely affected by climate impacts);
2. reduce sensitivity (that is, lower the degree to which a system is adversely affected by exposure to climate impacts); and

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

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

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

Adapting to Current Variability and Preparing for Future Change

Adaptation addresses two timescales: 1) adapting to current variability, which in any particular location may now be different than suggested by the historical record of climate observations, and 2) preparing for future change. This distinction is useful because

some decision-makers may not appreciate the extent to which climate has already changed and because these timescales often call for different types of adaptation actions.

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

These timescale differences relate to the ubiquitous term resilience⁵⁷ that is frequently employed in adaptation planning under a spectrum of meanings.^{58,59} These range from the ability to withstand and recover from current shocks and stressors while retaining basic functions under conditions of existing and near-term variability to the ability to transform in desirable ways over time as the magnitude of change increases.^{60,61,62,63,64,65} Recognizing these timescales in planning, and communicating expectations for change along those timelines,

can also help communities maximize benefits in the near term and identify the most important opportunities for longer-term well-being and resilience.

Organizations are increasingly exploring alternative approaches for replacing the assumption of an unchanging (or stationary) climate in their risk management activities. Vulnerability assessments, a common practice among managers of public lands and natural areas, often evaluate exposure, sensitivity, and adaptive capacity, and provide rankings of the seriousness of various climate risks. Multi-objective approaches, such as structured decision-making,⁶⁶ explicitly include multiple measures of well-being in risk assessment and management, often in difficult areas such as protecting cultural resources.⁴⁰ Scenarios are used to 1) assess risks over a range of plausible futures that include both changes in socioeconomic trends as well as climate and 2) choose adaptation actions robust over this wide range of futures.¹⁸ California's 2018 Sea-Level Rise Guidance includes probabilistic sea level rise projections and a worst-case scenario, then integrates both with an adaptive pathways approach⁶⁷ that encourages robust and flexible plans that can adjust over time if seas rise faster than expected.

Climate risk management requires addressing socioeconomic (for example, future economic, technology, and regulatory conditions) as well as climate uncertainties. Risk management can address such uncertainties, even when they are difficult to characterize with confidence (Ch. 17: Complex Systems, KM 3).^{42,68,69,70,71} The water sector is pioneering approaches for

incorporating such information in water utility adaptation, including scenarios and other robust decision methods aimed at making successful decisions insensitive to a wide range of uncertainty.⁷² Some agencies are beginning to combine both multi-objective and multi-scenario approaches in quantitative tools that identify vulnerabilities and evaluate tradeoffs among adaptive pathways, seeking risk management strategies that perform well across multiple scenarios and measures of well-being.^{73,74,75,76} Implementing such methods can require a more complete set of system models than some agencies commonly use in their planning routines, though such tools are becoming increasingly available.⁷⁷

Benefits of Adaptation Can Exceed the Costs

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

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

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

To date, there exists considerable guidance on actions in some sectors where benefits exceed costs, though guidance is lacking in many other sectors.⁸³ Benefit–cost information exists for adaptation responses to storms and rising seas in coastal zones, to riverine and extreme precipitation flooding, and for agriculture at the farm level.^{85,86} Some of the actions in these sectors, at least in some locations, appear to have large benefit–cost ratios, both in addressing current variability and in preparing for future change. A benefit–cost ratio greater than 1 suggests a promising project to undertake, because the benefits it generates are greater than its costs. For instance, while sandbags protecting individual houses can, in general, have benefit–cost ratios less than 1, in South Florida sandbags can have a benefit–cost ratio of 20 to 1,⁸⁷ and along the Gulf of Mexico coastline, 3 to 1.⁸⁸ Along the Gulf of Mexico coastline, levees and seawalls can have benefit–cost ratios ranging from 2.3 to 1.5 to 1 for refineries and petrochemical plants, though the ratios are lower for other assets.⁸⁸

Information on the cost of actions that can achieve common goals is increasing in the water management sector, such as for operational reliability and resilience and environmental protection (Ch. 3: Water) and

for responding to extreme heat events (Ch. 14: Human Health). Loss of water services or power during a high heat event, for example, can produce considerable costs that can have cascading effects on other sectors, thereby further driving up costs.⁸⁹ The benefits of these adaptive actions against these threats have been studied less because they involve societal and environmental impacts that have been more difficult to quantify, study, and describe systematically.

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

Extensive co-benefits may also be available from adaptation, in particular in the ecosystem services and health sectors (Ch. 7: Ecosystems; Ch. 14: Human Health). Coordinated adaptation and GHG mitigation planning may also provide defined co-benefits (Ch. 29: Mitigation, KM 4). For instance, tools are available to help

decision-makers locate wind energy systems away from sensitive ecological sites, without incurring additional costs (for example, see the Nature Conservancy's Biodiversity and Wind Siting Mapping Tool at <https://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newyork/climate-energy/working-with-wind.xml>). Designs that provide green space and the use of cool and green roof technologies in cities can reduce heat-island effects, producing multiple benefits and cost reductions by helping to reduce emissions and air pollution, human health risks, and economic losses due to reduced labor productivity.^{93,94}

Broader Measures of Well-Being

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

Considering various types of outcomes separately in risk management processes—termed multi-objective or multi-criteria analysis in the relevant literature⁹⁷—can facilitate

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

Risk management approaches that consider multiple objectives can include a specific focus on equity, with important implications on the content and process of adaptation planning and action.⁹⁹ Poor or marginalized populations often face a higher risk from climate change because they live in areas with higher exposure, are more sensitive to climate impacts, or lack adaptive capacity (Ch. 14: Human Health; Ch. 15: Tribes). Prioritizing adaptation actions for such populations may prove more equitable and lead, for instance, to improved infrastructure in their communities and increased focus on efforts to promote social cohesion and community resilience that can improve their capacity to prepare, respond, and recover from disasters. Equity considerations can also lead to the expanded participation of poor or marginalized populations in adaptation planning efforts. This can enhance the fairness of

the process. Moreover, it can positively affect choices regarding the appropriate balance among the resources invested in reducing climate risk and those put toward other social goals, such as employment and education, and inform the most appropriate mix of adaptation actions in each community.⁵² Also, at the state and national level, equity considerations for climate adaptation can help allocate an appropriate distribution of resources for adaptation among different local communities.

Key Message 5

New Approaches Can Further Reduce Risk

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

A significant portion of climate risk can be addressed by mainstreaming; that is, integrating climate adaptation into existing organizational and sectoral investments, policies, and practices. Mainstreaming can make adaptation more likely to succeed because it augments already familiar processes with new information and tools, rather than requiring extensive new structures.^{100,101,102} Mainstreaming can also encourage risk management actions that synergistically and coherently address adaptation along with other societal objectives. Mainstreaming can also prompt innovation in existing organizational structures^{103,104} by improving their treatment of all types of uncertainty. However, mainstreaming can diminish

the visibility of climate adaptation relative to dedicated, stand-alone adaptation approaches¹⁰⁵ and may prove insufficient to address the full range of climate risk, in particular the risks associated with higher GHG concentrations.

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

Existing Mainstreaming

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

A growing number of jurisdictions address climate risk in their land-use, hazard mitigation, capital improvement, and transportation plans. In 2015, FEMA began requiring states to include the projected effects of climate change in their state hazard mitigation plans.¹⁰⁶ A small number of cities explicitly link their coastal plans and their hazard mitigation plans using a common, climate-informed vulnerability analysis to support both types of plans, thereby ensuring that the different city agencies are implementing risk reduction measures—such as land-use measures (reducing exposure), building codes (reducing sensitivity), and warning, evacuation, and recovery measures

(increasing adaptive capacity)—that are synergistic and coordinated.¹⁰⁷ The City of Baltimore used climate-informed estimates of increased current and future storm intensity to design its storm water master plan, which includes green space and bio-swales that capture runoff, to improve water quality and reduce flood risk. California requires its water agencies to address climate change in their water management plans. Through the Department of Energy (DOE) Partnership for Energy Sector Climate Resilience, electric utilities across the country are collaborating with DOE to develop resilience planning guidance, conduct climate change vulnerability assessments, and develop and implement cost-effective resilience solutions (Ch. 4: Energy). The National Oceanic and Atmospheric Administration (NOAA), FEMA, and the U.S. Geological Survey are partnering with states to develop guidelines for integrated climate adaptation, land use, and hazard mitigation planning. Federal agencies have also begun implementing climate-smart management approaches for managing their natural resources (Ch. 7: Ecosystems, KM 2).

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

emerging risks associated with climate change^{110,111} and now embed these risks into their credit ratings.¹¹² In particularly vulnerable areas, such as South Florida, bond ratings are now beginning to reflect such risks.

The engineering community has begun incorporating climate resilience into its design standards by incorporating information about current and future climate threats and impacts¹¹³ and updating existing engineering standards, codes, regulations, and practices—currently based on stationary climate assumptions.¹¹⁴ The American Society of Civil Engineers (ASCE) recommends that engineers incorporate climate uncertainty, assess the costs of reducing risks, and follow an adaptive management process. Such a process would begin with low-regret strategies that perform well across a range of futures and periodically update as new information becomes available.¹¹³ The ASCE and the States of California and New York have formed committees to develop such standards.¹¹⁵

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

Overcoming Up-Front Challenges

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

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

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

investing in long-lived infrastructure designed for stationary conditions, as opposed to currently changing and future climate conditions.¹²⁴

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

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

enforcement, make decision-makers seem indecisive, and make it easier for them to succumb to political pressure from special interests.¹³⁰

Catalysts for Adaptation

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

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

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

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

Box 28.3: Common Attributes of Effective Adaptation

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

- plans written by a professional staff and approved by elected officials;
- community engagement, including the participatory development of plans; the formation of action teams or regional collaborations¹³⁸ across jurisdictions, sectors, and scales; and public- and private-sector leaders who champion and support the process;
- adaptation actions that address multiple community goals, not just climate change;
- well-structured implementation, including the identification of parties responsible for each step, explicit timelines, explicit and measurable goals, and explicit provisions and timelines for monitoring and updating the plan; and
- adequate funding for the adaptation actions and for sustained community outreach and deliberation.

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

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

Over the past several years, examples of sustained collaborative partnerships between research and management in support of climate risk management have included NOAA's Regional Integrated Sciences and Assessments (RISA), the U.S. Department of Agriculture's (USDA) Climate Hubs, and the Department of the Interior's (DOI) Climate Adaptation Science Centers (CASCs). These regional climate information networks provide data, tools, forecasts, interpretation, and extension services for agencies and communities to build into integrated services and work together to coordinate stakeholder engagement across multiple sectors as new knowledge emerges.^{150,151} Some examples include knowledge platforms, such as the Climate Adaptation Knowledge Exchange (www.cakex.org), the Georgetown Climate Center's Adaptation Clearinghouse (<http://www.adaptationclearinghouse.org/>), and the U.S. Climate Resilience Toolkit website (toolkit.climate.gov); these platforms include directories of practitioners and inventories of data tools for managing natural and built systems in the face of climate change.

More local, targeted resources, such as Louisiana's Coastal Protection Restoration Authority Master Plan Data Viewer (<http://cims.coastal.la.gov/masterplan/>), offer detailed information about climate risks and probabilities in specific geographic locations to help planners and communities better anticipate and prepare for climate impacts. Such initiatives and networks enable practitioners to share best practices and evaluate and inform adaptation implementation while empowering communities to advance preparedness and resilience efforts across the United States.

Beyond Incremental Change

Integrating climate risk into existing practices can lead to change that is more than incremental. For instance, it often proves profitable in the near term to build in low-lying areas subject to future extreme flooding¹⁵² rather than in areas with lower future risk. Updated flood maps and risk-adjusted insurance rates would likely lead to different patterns of development.¹⁵³ In many cases, however, addressing the full range of future climate change requires substantial changes in organizational practices and procedures, in public- and private-sector institutions, in individual and societal expectations and norms, in capital investment planning, and in laws.^{154,155} Decision-makers may wish to take active steps to anticipate and steer change in desired directions and to avoid the unanticipated consequences of ad hoc or crisis-based responses. In some cases, this involves seeking, legitimizing, and accelerating large changes, rather than attempting to retain today's conditions as long as possible.^{10,156,157}

Reducing climate risk often requires managing interdependent systems in ways that transcend current jurisdictional and sectoral boundaries (Ch. 4: Energy; Ch. 17: Complex Systems, KM 3). Water, electric power supply, and agriculture often depend critically on one another (see Ch. 17: Complex Systems, KM 1) but are not treated

similarly for potential adaptation actions. Effective climate risk management often requires closer coordination among regulatory agencies and, in some cases, may necessitate some restructuring. For instance, the City of Los Angeles's One Water LA program requires multiple city agencies to coordinate on integrated management of the city's water, land-use, and flood control actions.¹⁵⁸ Major reforms can prove difficult and often occur only in response to major system shocks, such as reforms to the Stafford Act after Hurricane Katrina^{159,160,161} or the consolidation of many local water agencies in Australia into a small number of large, regional organizations during a decade of severe drought.¹⁶²

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

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

Acknowledgments

Technical Contributors

Lauren Kendrick

RAND Corporation

Pat Mulroy

Brookings Institution

Costa Samaras

Carnegie Mellon University

Bruce Stein

National Wildlife Federation

Tom Watson

The Center for Climate and Security

Jessica Wentz

Columbia University

USGCRP Coordinators

Sarah Zerbonne

Adaptation and Decision Science Coordinator

Fredric Lipschultz

Senior Scientist and Regional Coordinator

Opening Image Credit

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Traceable Accounts

Process Description

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

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

Key Message 1

Adaptation Implementation Is Increasing

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

Description of evidence base

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

Major uncertainties

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

adaptation activities with what might be appropriate according to some normative standard or what might be reasonably achieved. Thus, while adaptation activities are clearly increasing in the United States, scant evidence exists for judging their consequences.

Description of confidence and likelihood

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

Key Message 2

Climate Change Outpaces Adaptation Planning

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

Description of evidence base

The assumption that the historical record of events and variability will be the same in the future is called the stationarity assumption²⁷ and has guided planning for climate and weather events in most places for most of recorded history. The evidence is strong that the stationarity assumption is no longer valid for all impacts and variability in all locations, because climate change is altering both the events and their variability.^{3,4,28,165} Regional chapters in this assessment establish the climate variables for which, and the extent to which, non-stationarity has been confirmed around the United States. These chapters also provide extensive documentation of cases in which failure to adapt to current and future climate conditions can cause significant adverse impacts.

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 3

Adaptation Entails Iterative Risk Management

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

Description of evidence base

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 4

Benefits of Proactive Adaptation Exceed Costs

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

Description of evidence base

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 5

New Approaches Can Further Reduce Risk

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

Description of evidence base

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

Major uncertainties

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

Description of confidence and likelihood

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

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Reducing Risks Through Emissions Mitigation

Federal Coordinating Lead Author**Jeremy Martinich**

U.S. Environmental Protection Agency

Chapter Lead**Jeremy Martinich**

U.S. Environmental Protection Agency

Chapter Authors**Benjamin DeAngelo**

National Oceanic and Atmospheric Administration

Delavane Diaz

Electric Power Research Institute

Brenda Ekwurzel

Union of Concerned Scientists

Guido Franco

California Energy Commission

Carla Frisch

U.S. Department of Energy

James McFarland

U.S. Environmental Protection Agency

Brian O'NeillUniversity of Denver (National Center for
Atmospheric Research through June 2018)**Review Editor****Andrew Light**

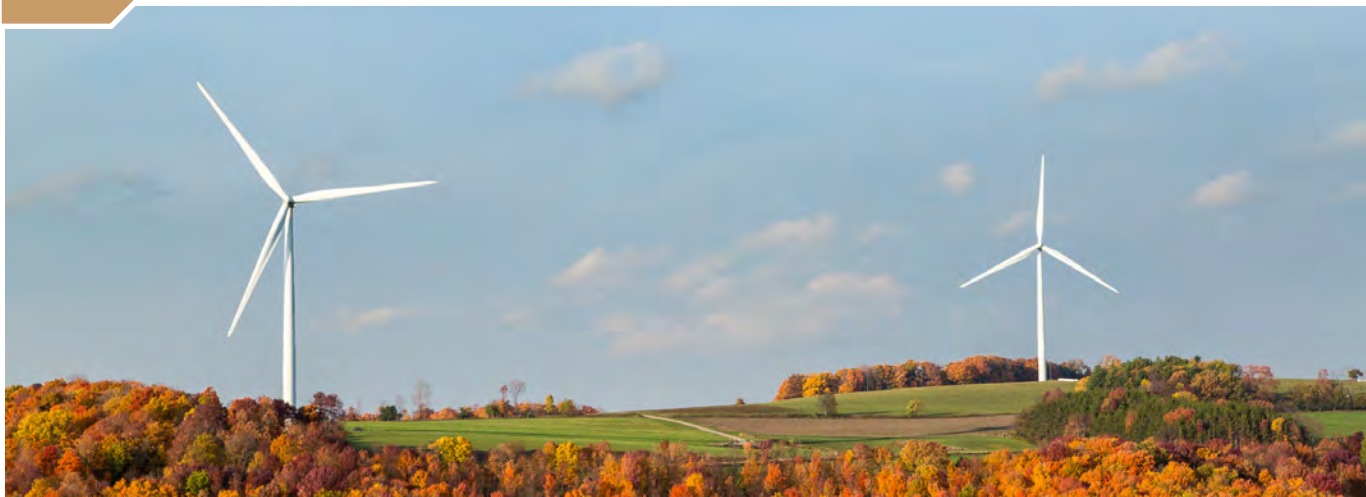
George Mason University

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Reducing Risks Through Emissions Mitigation



Key Message 1

Jasper, New York

Mitigation-Related Activities Within the United States

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

Key Message 2

The Risks of Inaction

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

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

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

Key Message 4

Interactions Between Mitigation and Adaptation

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

Executive Summary

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

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

health.^{2,3,4,5} For sectors where positive effects are observed in some regions or for specific time periods, the effects are typically dwarfed by changes happening overall within the sector or at broader scales.

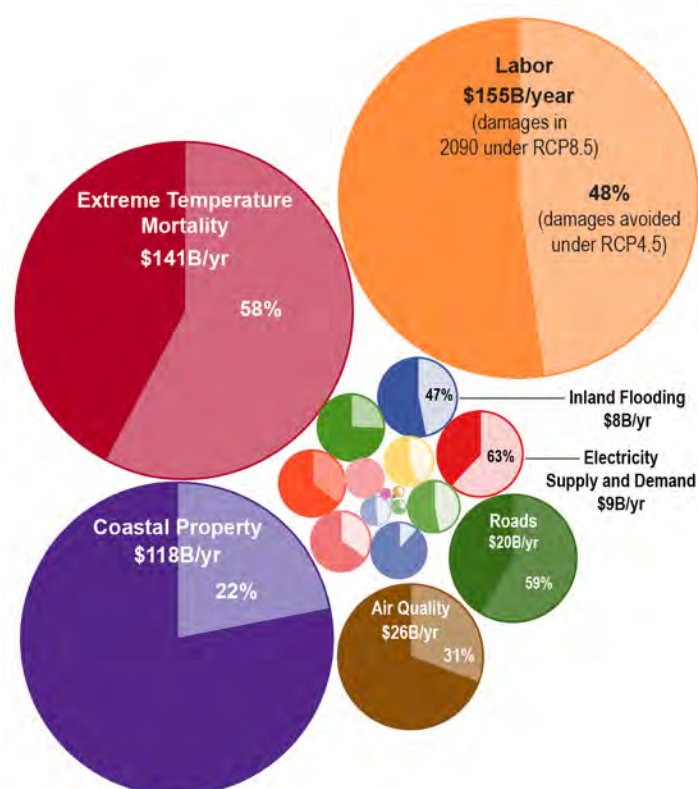
Recent studies also show that many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions. While the difference in climate outcomes between scenarios is more modest through the first half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

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population. Physical damages to coastal property and transportation infrastructure are particularly sensitive to adaptation assumptions, with proactive measures estimated to be capable of reducing damages by large fractions. Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and

adaptation activities can be considered complementary strategies. However, adaptation can require large up-front costs and long-term commitments for maintenance, and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk. Interactions between adaptation

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

Projected Damages and Potential for Risk Reduction by Sector



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

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

Introduction

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

Carbon Cycle Report.¹³ Further, it is beyond the scope of this chapter and this assessment to evaluate or recommend policy options.

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

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

Box 29.1: Options for Reducing or Removing Greenhouse Gases

Mitigation refers to measures to reduce the amount and speed of future climate change by reducing emissions of greenhouse gases (GHGs) or by increasing their removal from the atmosphere. Emission reduction measures include replacing conventional, CO₂-emitting fossil fuel energy technologies or systems with low- or zero-emissions ones (such as wind, solar, nuclear, biofuels, fossil energy with carbon capture and storage, and energy efficiency measures), as well as changing technologies and practices in order to lower emissions of other GHGs such as methane, nitrous oxide, and hydrofluorocarbons.^{7,14,15} Measures that enhance the removal of CO₂ from the atmosphere (see Box 29.3) include changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO₂ through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO₂.¹⁶ Using captured CO₂ in products such as polymers and cement is a potential alternative to geologic storage.¹⁷

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

Timing and Magnitude of Action

Current and future emissions, and thus emissions mitigation actions, are crucial for determining future risks and impacts. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those emissions reductions, and the relative mix of mitigation strategies for emissions of long-lived GHGs (namely, CO₂), short-lived GHGs (such as methane), and land-based biogenic carbon.¹ Intentional removal of CO₂ from the atmosphere, often referred to as negative emissions, or other climate interventions have also been proposed^{10,18} and may play a role in future mitigation strategies (see Box 29.3).

Net cumulative CO₂ emissions in the industrial era will largely determine long-term global average temperature change⁹ and thus the risks and impacts associated with that change in the climate. Large reductions in present-day emissions of the long-lived GHGs are estimated to have modest temperature effects in the near term (over the next couple decades), but these emission reductions are necessary to achieve any long-term objective of preventing warming of any desired magnitude.⁹ Decisions that decrease or increase emissions over the next few decades will set into motion the degree of impacts that will likely last throughout the rest of this century, with some impacts (such as sea level rise) lasting for thousands of years or even longer.^{19,20,21}

Meeting any climate stabilization goal, such as the oft-cited objective of limiting the long-term globally averaged temperature to 2°C (3.6°F) above preindustrial levels, necessitates that there be a physical upper limit on the cumulative amount of CO₂ that can be added to the atmosphere.⁹ Early and substantial mitigation offers a greater chance for achieving a long-term goal, whereas delayed and

potentially much steeper emissions reductions jeopardize achieving any long-term goal given uncertainties in the physical response of the climate system to changing atmospheric CO₂, mitigation deployment uncertainties, and the potential for abrupt consequences.^{11,22,23} Early efforts also enable an iterative approach to risk management, allowing stakeholders to respond to what is learned over time about climate impacts and the effectiveness of available actions (Ch. 28: Adaptation).^{24,25,26} Evidence exists that early mitigation can reduce climate impacts in the nearer term (such as reducing the loss of perennial sea ice and effects on ice-dwelling species) and, in the longer term, prevent critical thresholds from being crossed (such as marine ice sheet instability and the resulting consequences for global sea level change).^{27,28,29,30}

State of Emissions Mitigation Efforts

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

Long-Term Temperature Goals and the Paris Agreement

The idea of limiting globally averaged warming to a specific value has long been examined in the scientific literature and, in turn, gained attention in policy discourse (see DeAngelo et al. 2017 for additional information⁹). Most recently, the Paris Agreement of 2015 took on the long-term aims of “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”.³¹ These targets were developed with the goal of avoiding the most severe climate impacts; however, they should not be viewed as thresholds below which there are zero risks and above which

numerous tipping points occur (that is, a point at which a change in the climate triggers a significant environmental event, which may be permanent). In order to reach the Paris Agreement's long-term temperature goal, Parties to the Agreement "aim to reach global peaking of GHG emissions as soon as possible . . . and to undertake rapid reductions thereafter." Many countries announced voluntary, nonbinding GHG emissions reduction targets and related actions in the lead-up to the Paris meeting; these announcements addressed emissions through 2025 or 2030 and took a range of forms.³¹ The Paris Agreement has been ratified by 180 Parties to the UN Framework Convention on Climate Change, which account for 88% of global GHG emissions.^{32,33}

Achieving the Paris Agreement target of limiting global mean temperature to less than 2°C (3.6°F) above preindustrial levels requires substantial reductions in net global CO₂ emissions prior to 2040 relative to present-day values and likely requires net CO₂ emissions to become zero or possibly negative later in the century, relying on as-yet unproven technologies to remove CO₂ from the atmosphere. To remain under this temperature threshold with two-thirds likelihood, future cumulative net CO₂ emissions would need to be limited to approximately 230 gigatons of carbon (GtC), an amount that would be reached in roughly the next two decades assuming global emissions follow the range between the RCP4.5 and RCP8.5 scenarios.⁹ Achieving global GHG emissions reduction targets and actions announced by governments in the lead-up to the 2015 Paris climate conference would hold open the possibility of meeting the 2°C (3.6°F) temperature goal, whereas there would be virtually no chance if net global emissions followed a pathway well above those implied by country announcements.⁹

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

Key Message 1

Mitigation-Related Activities Within the United States

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

Many activities within the public and private sectors either aim to or have the effect of reducing these emissions. Fossil fuel combustion accounts for 77% of the total U.S. GHG emissions (using the 100-year global warming potential), with agriculture, industrial processes, and methane from fossil fuel extraction and processing as well as waste accounting for the remainder.³⁷ A 100-year global warming potential is an index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over one hundred years, relative to that of the reference substance, CO₂.³⁸ At the federal level, a number of measures have been implemented to promote advanced, low-carbon energy technologies and fuels, including energy efficiency. Broadly considered, these measures include

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

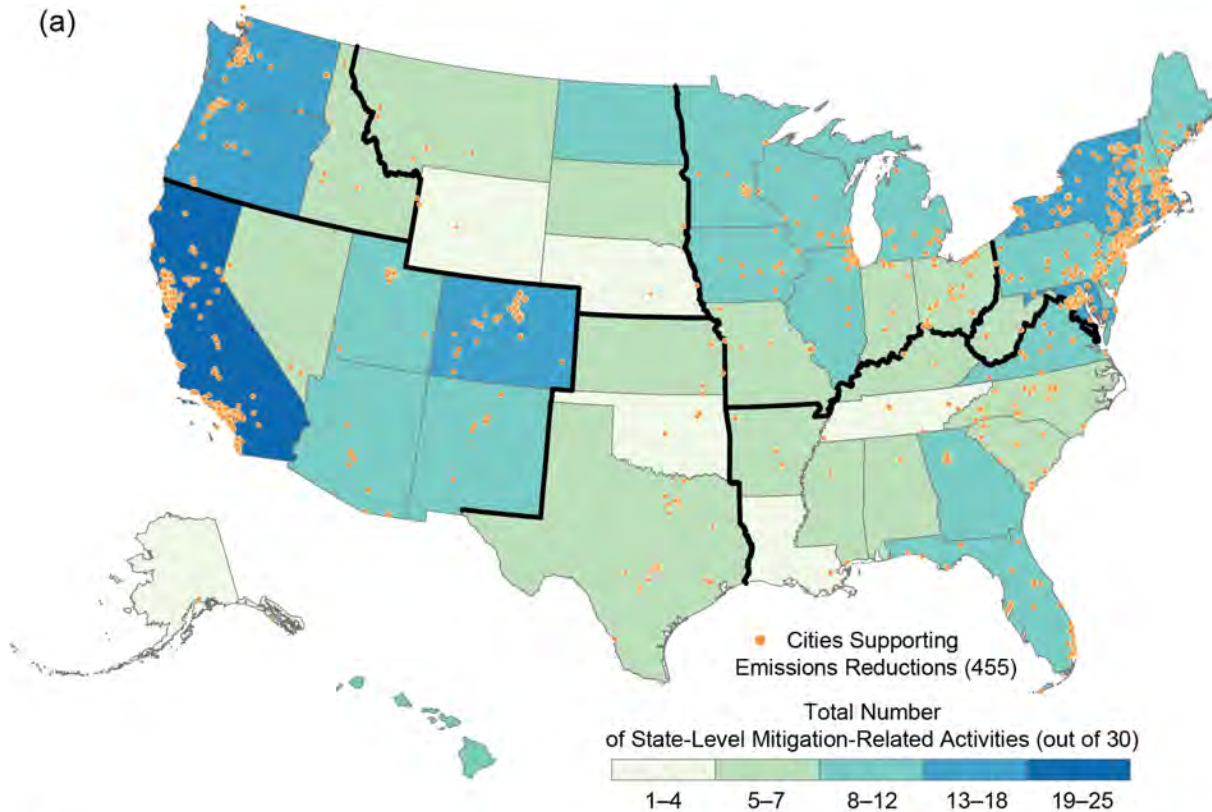
State, local, and tribal government mitigation approaches include comprehensive emissions reduction strategies as well as sector- and technology-specific policies designed for many reasons. As shown in Figure 29.1a, at least 455 cities support emissions reductions in the context of global efforts, including 110 with emissions reduction targets.³⁶ At the state level, the color shown on each state indicates the total number of activities taken in that state across six policy areas: GHG target/cap/ pricing; renewable/carbon dioxide capture and storage (CCS)/nuclear; transportation; energy efficiency; non-CO₂ GHG; and forestry and land use.³⁶ Figure 29.1b shows the number of activities by policy area for each state. For example, states in the Northeast take part in the Regional Greenhouse Gas Initiative, a mandatory market-based effort to reduce power sector emissions.⁴¹ California has a legal mandate to reduce emissions 40% below 1990 levels by 2030, and in a 2017 law, the

state extended its emissions trading program to 2030, as well. Several states have adopted voluntary pledges to reduce emissions. Technology-specific approaches include targets to increase the use of renewable energy such as wind and solar, zero- or low-emissions transportation options, and energy efficient technologies and practices.^{42,43} Many tribes are also prioritizing energy-efficiency and renewable-energy projects (Ch. 15: Tribes, KM 1).⁴⁴ Mitigation activities related to methane and forestry/land-use activities are growing in number and vary by locale.

In the private sector, many companies seek to provide environmental benefits for a variety of reasons, including supporting environmental stewardship, responding to investor demands for prudent risk management, finding economic opportunities in efforts to reduce GHG emissions, and, in the case of multinationals, meeting mitigation mandates in the European Union or other jurisdictions. Since the last National Climate Assessment, private companies have increasingly taken inventory of their emissions and moved forward to implement science-based emissions reduction targets as well as internal carbon prices.³⁶ The Carbon Disclosure Project⁴⁶ is one example of a voluntary program where companies register their pledges to reduce GHG emissions and/or to manage their climate risks. Corporate purchases of and commitments to purchase renewable energy have increased over the last decade.⁴⁷

Mitigation-Related Activities at State and Local Levels

(a)



(b)

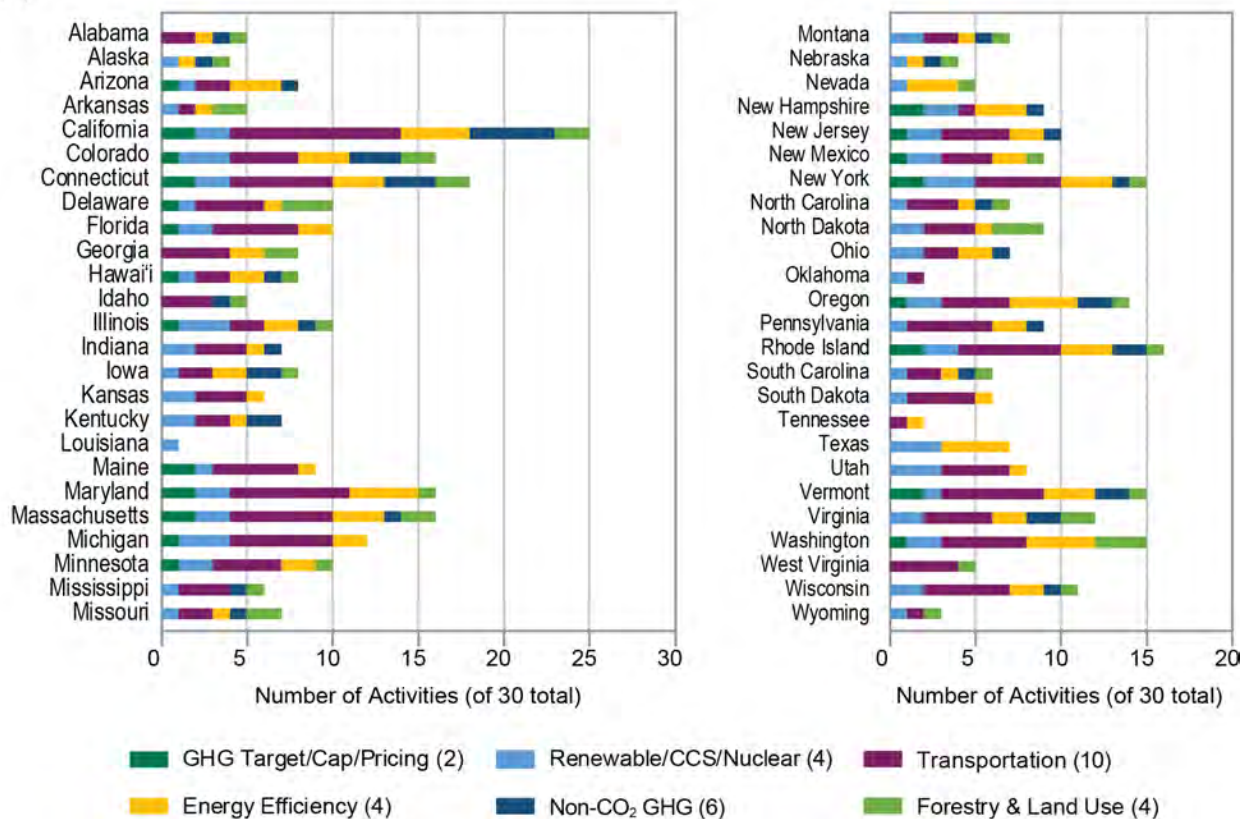


Figure 29.1: The map (a) shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; the chart (b) depicts the type and number of activities by state.³⁶ Several territories also have a variety of mitigation-related activities including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands.^{42,45} Sources: (a) EPA and ERT, Inc.; (b) adapted from America's Pledge 2017.³⁶ This figure was revised in June 2019. See Errata for details: <https://nca2018.globalchange.gov/downloads>

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. GHG emissions over the past decade. In 2016, U.S. emissions were at their lowest levels since 1994.³⁷ Power sector emissions were 25% below 2005 levels in 2016, the largest sectoral reduction over this time.³⁷ This decline was in large part due to increases in natural gas generation as well as renewable energy generation and energy efficiency (Ch. 4: Energy, KM 2).⁴⁸ Given these changes in the power sector, the transportation sector currently has the largest annual sectoral emissions (Ch. 12: Transportation). As of the writing of this report, projections of U.S. fossil fuel CO₂ and other GHG emissions show flat or declining trajectories over the next decade, with a central estimate of about 15%–20% below 2005 levels by 2025.^{49,50} Prior to the adoption of the Paris Agreement, the United States put forward a nonbinding “intended nationally determined contribution” of reducing emissions 26%–28% below 2005 levels in 2025. On June 1, 2017, President Trump announced that the United States would cease implementation of this nationally determined contribution. Some state and local governments, as well as private-sector entities, have announced emission reduction pledges which aim to be consistent with the nonbinding target.^{35,36} For more information on trends in, drivers of, and potential efforts to address U.S. GHG emissions, see the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.³⁷

Reducing Impacts Through Mitigation

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

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

Table 29.1: Selection of Multisector Impacts Modeling Frameworks Since NCA3. Source: adapted from Diaz and Moore 2017.⁵⁴

Key Message 2

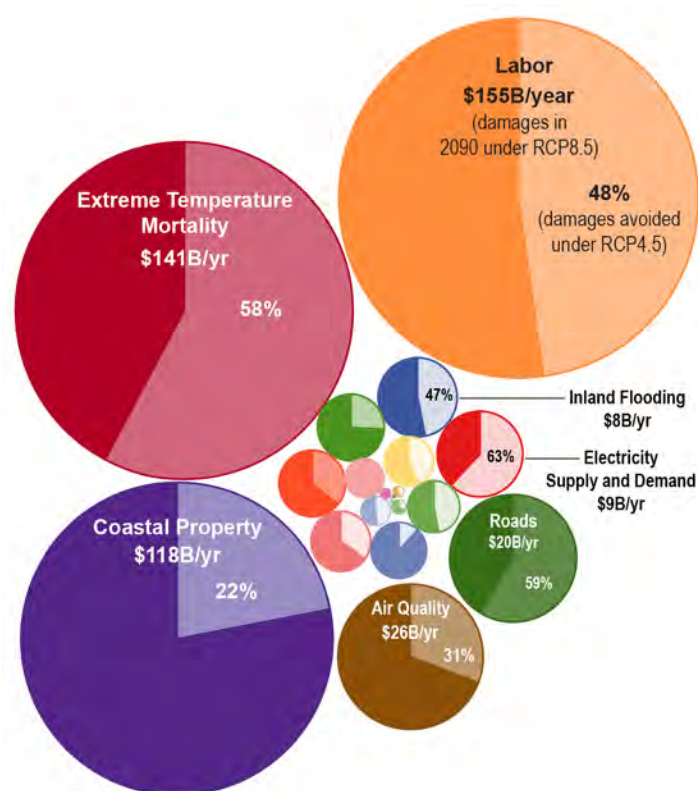
The Risks of Inaction

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

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high GHG emissions, such as RCP8.5, and under scenarios with limited or no adaptation (for more on RCPs, see the Scenario Products section of App. 3).⁶⁴ Recent findings from multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly towards the end of the century—with negative consequences for a large majority of sectors. Moreover, the impacts and costs of climate change are already being felt in the United States, and recent extreme weather and climate-related events can now be

attributed with increasingly higher confidence to human-caused warming.⁶⁵ Impacts associated with human health, such as premature mortality due to extreme temperature and poor air quality, are commonly some of the most economically substantial (Ch. 13: Air Quality; Ch. 14: Human Health).^{2,3,4,5} While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources.^{66,67} Further, some impacts will very likely be irreversible for thousands of years, including those to species, such as corals (Ch. 9: Oceans; Ch. 27: Hawai'i & Pacific Islands),^{1,2,68} or those that involve the exceedance of thresholds, such as the effects of ice sheet disintegration on accelerated sea level rise, leading to widespread effects on coastal development lasting thousands of years.^{69,70,71} Figure 29.2 shows that climate change is projected to cause damage across nearly all of the sectors analyzed. The conclusion that climate change is projected to result in adverse impacts across most sectors is consistently found in U.S.-focused multisector impact analyses.^{2,3,4,5} For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).^{2,3,4,5}

Projected Damages and Potential for Risk Reduction by Sector



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

Figure 29.2: The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.² Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. Source: adapted from EPA 2017.²

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

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

Many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in GHG emissions (Figure 29.2). While the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,⁶ the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter.^{2,3,4} For some sectors, this creates large projected benefits of mitigation. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (overall) thousands to tens of thousands of deaths per year from extreme temperatures (Ch. 14: Human Health),^{2,3,5} hundreds to thousands of deaths per year from poor air quality (Ch. 13: Air Quality),^{2,72} and the annual loss of hundreds of millions of labor hours from extreme temperatures.^{2,3} When monetized, each of these avoided health impacts represents domestic economic benefits of mitigation on the order of tens to hundreds of billions of dollars per year.^{2,3,73} For example, Figure 29.2 shows that reduced emissions under RCP4.5

can avoid approximately 48% (or \$75 billion) of the \$155 billion in lost wages per year by 2090 due to the effects of extreme temperature on labor (for example, outdoor industries reducing total labor hours during heat waves). Looking at the economy as a whole, mitigation can substantially reduce damages while also narrowing the uncertainty in potential adverse impacts (Figure 29.3).

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

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

Estimates of Direct Economic Damage from Temperature Change

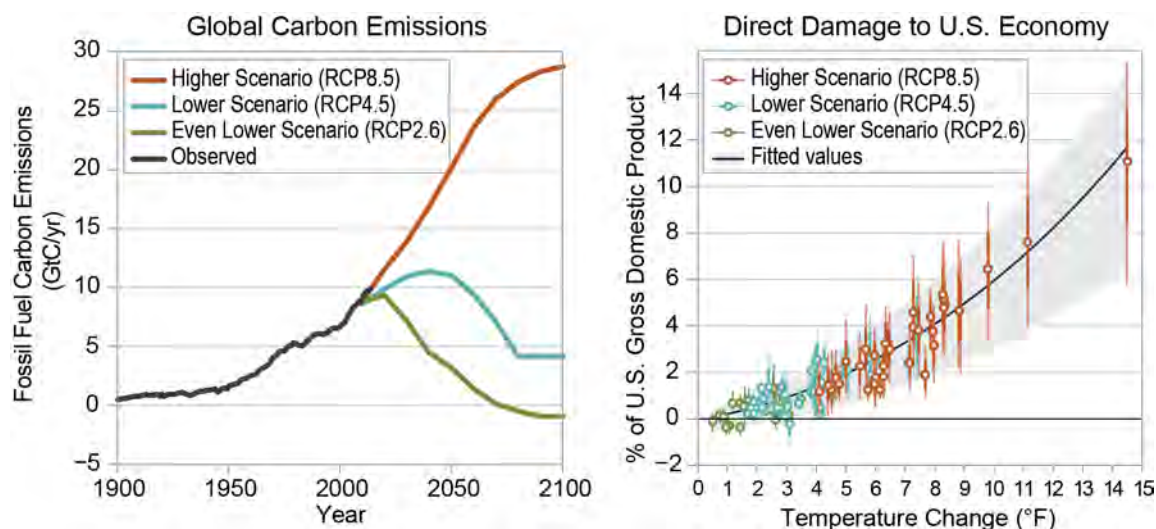


Figure 29.3: The left graph shows the observed and projected changes in fossil fuel and industrial emissions of CO₂ from human activities (emissions from land-use change do not appear in the figure; within the RCPs these emissions are less than 1 GtC per year by 2020 and fall thereafter). The right graph shows projections of direct damage to the current U.S. economy for six impact sectors (agriculture, crime, coasts, energy, heat mortality, and labor) as a function of global average temperature change (represented as average for 2080–2099 compared to 1980–2010). Compared to RCP8.5, lower temperatures due to mitigation under either of the lower scenarios (RCP2.6 or RCP4.5) substantially reduce median damages (dots) to the U.S. economy while also narrowing the uncertainty in potential adverse impacts. Dot-whiskers indicate the uncertainty in direct damages in 2090 (average of 2080–2099) derived from multiple combinations of climate models and forcing scenarios (dot, median; thick line, inner 66% credible interval; thin line, inner 90%). The gray shaded area represents the 90% confidence interval in the fit (black line) to the damage estimates. Damage estimates only capture adaptation to the extent that populations employed them in the historical period. Sources: (left) adapted from Wuebbles et al. 2017;⁸³ (right) adapted from Hsiang et al. 2017³ and republished with permission of American Association for the Advancement of Science.

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

The marginal benefit, equivalently the avoided damages, of mitigation can be expressed as the social cost of carbon (SCC). The SCC is a monetized estimate of the long-term climate damages to society from an additional amount of CO₂ emitted and includes impacts that accrue in market sectors such as agriculture, energy services, and coastal resources, as well as nonmarket impacts on human health and ecosystems.^{84,85} This metric is used to inform climate risk management decisions at national, state, and corporate levels.^{86,87,88,89,90} Notably, estimating the SCC depends on normative social values such as time preference, risk

aversion, and equity considerations that can lead to a range of values. In recognition of the ongoing examination about existing approaches to estimating the SCC,^{91,92,93} a National Academies of Sciences, Engineering, and Medicine report⁹⁴ recommended various improvements to SCC models, including that they 1) be consistent with the current state of scientific knowledge, 2) characterize and quantify key uncertainties, and 3) be clearly documented and reproducible.

Although uncertainties still remain, advancements in climate impacts and economics modeling are increasingly providing new capabilities to quantify future societal effects of climate change. A growing body of studies use and assess statistical relationships between observed socioeconomic outcomes and weather or climate variables to estimate the impacts of climate change (e.g., Müller et al. 2017, Hsiang et

al. 2017^{3,95}). In the United States, in particular, the rise of big data (large volumes of data brought about via the digital age) and advanced computational power offer potential improvements to study climate impacts in many sectors like agriculture, energy, and health, including previously omitted sectors such as crime, conflict, political turnover, and labor productivity. Parallel advancements in high-resolution integrated assessment models (those that jointly simulate changes in physical and socioeconomic systems), as well as process-based sectoral models (those with detailed representations of changes in a single sector), enable impact projections with increased regional specificity, which across the modeling frameworks shown in Table 29.1 reveal complex spatial patterns of impacts for many sectors. For example, this spatial variability is consistently observed in the agriculture sector,^{2,5,96,97} where the large number of domestic crops and growing regions respond to changes in climate and atmospheric CO₂ concentrations in differing ways. As such, the benefits of mitigation for agriculture can vary substantially across regions of the United States and summing regional results into national estimates can obscure important effects at the local level.

Key Message 4

Interactions Between Mitigation and Adaptation

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

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

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

Adaptation and mitigation strategies can also interact, with the potential for benefits

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

In buildings and industrial facilities, adaptation measures such as investments in energy efficiency (for example, through efficient building

materials) would reduce building energy demand (and therefore emissions), as well as lessen the impacts of extreme heat events.^{112,113}

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

Box 29.2: Co-Effects of Mitigation Actions

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

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

Box 29.3: Reducing Risk Through Climate Intervention

Climate intervention techniques (or geoengineering) are aimed at limiting global or regional temperature increase by affecting net radiative forcing through means other than emissions reductions (for a more detailed discussion see DeAngelo et al. 2017⁹). There are two broad categories of climate intervention techniques. One is carbon dioxide removal (CDR), which would reduce atmospheric CO₂ concentrations by changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO₂ through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO₂.¹⁶ The second is solar radiation management (SRM), which would increase Earth's regional and/or global reflectivity by, for example, injecting sulfur gases or other substances into the stratosphere or brightening marine clouds. CDR is estimated to have long implementation times, and while costs (and their uncertainties) range widely across different measures,¹³⁴ it is estimated to be expensive at scale.¹⁰ Nonetheless, large-scale CDR can be competitive with more traditional GHG mitigation options when substantial mitigation is required, and therefore it is an element of many scenarios that feature deep emissions reductions or negative emissions. Its climate benefits are likely to be similar to those from emissions reductions since both strategies act through reduced atmospheric concentrations of GHGs. Studies point to the risks of reaching the limits of available land, water, or biogeochemical requirements of biomass-based approaches at scale sufficient to offset large emissions.^{13,16,99,135,136} In contrast to CDR, SRM strategies are estimated to be relatively inexpensive and realize climate benefits within a few years. They could be targeted at regional as well as global temperature modification¹³⁷ and could be combined with mitigation to limit the rate or the peak magnitude of warming. However, SRM effects on other outcomes, including precipitation patterns, light availability, and atmospheric circulation, are less well understood. In addition, SRM would not reduce risks from increasing atmospheric CO₂ concentra-

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

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

Direction for Future Research**Coordinated Impacts Modeling Analyses**

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

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

Advancements to Address Research Needs from the Third National Climate Assessment

While not an exact analog to this chapter, the Third National Climate Assessment (NCA3)¹⁴⁰ included a Research Needs chapter

as part of the Response Strategies section that recommended five research goals: 1) improve understanding of the climate system and its drivers, 2) improve understanding of climate impacts and vulnerability, 3) increase understanding of adaptation pathways, 4) identify the mitigation options that reduce the risk of longer-term climate change, and 5) improve decision support and integrated assessment.¹⁴¹ Several of these topics have seen substantial advancements since publication of NCA3, informing our understanding of avoided climate risks. For example, research findings related to climate system drivers and the characterization of uncertainty have helped to differentiate the physical and economic outcomes along alternative mitigation pathways.^{3,20,30} Enormous growth in impacts, adaptation, and vulnerability (IAV) research has enabled more robust quantification of the relative impacts (avoided damages) corresponding to different climate outcomes. However, challenges remain in accounting for the reduced risks and impacts associated with nonlinearities in the climate system, including tipping points such as destabilization of the West Antarctic ice sheet or rapid methane release from thawing permafrost.^{22,98,142,143} Mitigation options continue to be studied to better understand their potential role in meeting different climate targets, and while many low-emitting or renewable technologies have seen rapid penetration, other strategies involving negative-emissions technologies have prompted caution due to the challenges of

achieving widespread deployment at low cost. Adaptation pathways are better understood but continue to be a source of uncertainty related to understanding climate risk and local adaptation decision-making processes. Decision support for climate risk management, especially under uncertainty, is an area of active research,^{144,145} and despite the limitations of integrated assessment models,^{146,147} they offer useful insights for decision-makers.¹⁴⁸

Remaining Knowledge Gaps

Despite ongoing progress, this assessment finds that significant knowledge gaps remain in many of the research goals and foundational crosscutting capabilities identified in NCA3. Going forward, it will be critically important to reduce uncertainties under different mitigation scenarios in 1) avoided sectoral impacts, such as agriculture and health, and 2) the capacity for adaptation to reduce impacts. Gaps in information on social vulnerability and exposure continue to hamper progress on disaster risk reduction associated with climate impacts.⁵¹ Directions for future research in the climate science and impacts field include improved understanding of the avoided/increased risk of thresholds, tipping points, or irreversible outcomes (see Kopp et al. 2017²²). Specific examples deserving further study include marine ice sheet instability and transformation of specific terrestrial carbon sinks into sources of greenhouse gas emissions.^{149,150}

Gaps remain in quantifying combined impacts and natural feedbacks. For example, coral reef health includes combined stress/relief from changes in local activities (for example, agricultural and other nutrient runoff and fishery

management), ocean acidification, ocean temperature, and the ability of coral species to adapt to changing conditions or repeated extreme events.^{151,152} Additional knowledge gaps include an understanding of how mitigation and adaptation actions affect climate outcomes due to interactions in the coupled human–earth system.^{142,153}

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

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USGCRP Coordinators

David Reidmiller
Director

Christopher W. Avery
Senior Manager

Opening Image Credit

Jasper, NY: © John Gretchel/Flickr (CC BY-NC 2.0). Adaptation: cropped top and bottom to conform to the size needed for publication.

Traceable Accounts

Process Description

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

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

Key Message 1

Mitigation-Related Activities Within the United States

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

Description of evidence base

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

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

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

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

U.S. companies that report through the Carbon Disclosure Project increasingly (although not comprehensively) reported board-level oversight on climate issues, which rose from 50% in 2011 to 71% in 2017. Likewise, 59 U.S. companies recently committed to set science-based emissions reduction targets.⁴⁶ U.S. businesses are increasingly pricing carbon.^{46,160} Corporate procurement of utility-scale solar has grown by an order of magnitude since 2014.⁴⁷

As indicated in the Education Institutions Reporting Database, a growing number of universities have made emissions reduction commitments or deepened existing commitments¹⁶¹ as well as publicized the progress on their efforts.¹⁶²

Major uncertainties

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

Description of confidence and likelihood

There is *very high confidence* that state, local, and private entities are increasingly taking, or are committed to taking, GHG mitigation action. Public statements and collated indices show an

upward trend in the number of commitments, as well as the breadth and depth of commitments over the past five years.

Key Message 2

The Risks of Inaction

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

Description of evidence base

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

There is robust and consistent evidence that climate change is projected to adversely affect many components of the U.S. economy. Increasing temperatures, sea level rise, and changes in extreme events are projected to affect the built environment, including roads, bridges, railways, and coastal development. For example, coastal high tide flooding is projected to significantly increase the hours of delay for vehicles.¹⁶³ Annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of the century under RCP8.5 (Ch. 8: Coastal).^{2,5} Projected annual repair costs in order for roads, bridges, and railways to maintain levels of service in light of climate change range in

the billions to tens of billions of dollars under RCP8.5.^{2,164} Numerous studies suggest that regional economies can also be at risk, especially when they are tied to environmental resources or ecosystem services that are particularly vulnerable to climate change. For example, projected declines in coral reef-based recreation^{152,165,166} would lead to decreases in tourism revenue; shorter seasons for winter recreation would likely lead to the closure of ski areas and resorts;^{167,168,169,170} and increased risks of harmful algal blooms can limit reservoir recreation (Ch. 3: Water).^{171,172}

An increasing body of literature indicates that impacts to human health are likely to have some of the largest effects on the economy. Studies consistently indicate that climate-driven changes to morbidity and mortality can be substantial.^{72,100,173,174,175,176} In some sectors, the value of health damages is estimated to reach hundreds of billions of dollars per year under RCP8.5 by the end of the century. A large fraction of total health damages is due to mortality, quantified using the Value of a Statistical Life (VSL) approach based on standard VSL values used in federal government regulatory analysis.¹⁷⁷ For example, annual damages associated with extreme temperature-related deaths are estimated at \$140 billion by the end of the century under RCP8.5, while lost wages from extreme temperatures, especially for outdoor industries, are projected at \$160 billion per year by 2090.² Adaptive actions, including physiological adaptation and increased availability of air conditioning, are projected to reduce extreme temperature mortality by approximately half; however, the implementation costs of those adaptations were not estimated. Although less studied compared to the research on the direct effects of temperature on health, climate-driven impacts to air quality^{72,178} and aeroallergens^{173,179} are also projected to have large economic effects, due to increases in medical expenditures (such as emergency room visits) and premature mortality (Ch. 13: Air Quality).

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

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

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

Description of evidence base

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

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

The finding that the magnitude and timing of avoided risks vary by sector and region, as well as due to changes in socioeconomics and adaptive capacity, is consistently supported by the broad literature base of multisector analyses (e.g., Hsiang et al. 2017, O'Neill et al. 2017, EPA 2017, Houser

et al. 2015^{2,3,4,5}) and focused sector studies (e.g., Melvin et al. 2016, Neumann et al. 2014^{71,77}). Complex spatial patterns of avoided risks are commonly observed across sectors, including for human health effects (e.g., Fann et al. 2015, Sarofim et al. 2016^{100,178}), agriculture (e.g., Beach et al. 2015¹⁹²), and water resources (e.g., Chapra et al. 2017, Wobus et al. 2017, EPA 2013^{167,171,193}).

The weight of evidence among studies in the literature indicates that the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,^{2,4,5,9} as the human-forced response may not yet have emerged from the noise of natural climate variability.⁶ In evaluating and quantifying multisector impacts across alternative scenarios, the literature generally shows that the effect of near-term mitigation in avoiding damages increases substantially in magnitude after 2050.^{2,4,5} For example, mitigation under RCP4.5 is projected to reduce the number of premature deaths and lost labor hours from extreme temperatures by 24% and 21% (respectively) by 2050, and 58% and 48% by 2090.² For coastal impacts, where inertia in the climate system leads to smaller differences in rates of sea level rise across scenarios, the effects of near-term mitigation only become evident toward the end of the century (Ch. 8: Coastal).^{2,5,19}

Major uncertainties

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

Description of confidence and likelihood

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

Key Message 4

Interactions Between Mitigation and Adaptation

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

Description of evidence base

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

Because of adaptation's ability to reduce risk in ways that mitigation cannot, and vice versa, the weight of the evidence shows that the two strategies can act as complements. Several recent studies jointly model the effects of mitigation and adaptation in reducing overall risk to the impacts of climate change in the United States, focusing on infrastructure (e.g., Larsen et al. 2017, Melvin et al. 2016, Neumann et al. 2014^{71,77,195}) and agriculture (e.g., Kaye and Quemada 2017, Challinor et al. 2014, Lobell et al. 2013^{108,109,111}). Exploration of this mitigation and adaptation nexus is also advancing in the health sector, with both mitigation and adaptation (such as behavioral changes or physiological acclimatization) being projected to reduce deaths from extreme temperatures¹⁰⁰ in both the higher and lower emissions scenarios that are the focus of this chapter. Similarly, energy efficiency investments are reducing GHG emissions and operating costs and improving resilience to future power interruptions from extreme weather events (Ch. 14: Human Health). While more studies exploring the joint effects of mitigation and adaptation are needed, recent literature finds that combined mitigation and adaptation actions can substantially reduce the risks posed by climate change in several sectors.^{2,103,104} However, several studies highlight that mitigation and adaptation can also interact negatively. While these studies are more limited in the literature, sectors exhibiting potential negative co-effects from mitigation and adaptation include the bioenergy–water resource nexus¹¹⁴ and changes in electricity demand and supply in response to increased use of air conditioning.^{2,117}

Major uncertainties

It is well understood that adaptation will likely reduce climate risks and that adaptation and mitigation interact. However, there are uncertainties regarding the magnitude, timing, and regional/sectoral distribution of these effects. Developing a full understanding of the interaction between

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

Description of confidence and likelihood

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

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Appendix 1. Report Development Process

Assessments are essential tools for linking science and decision-making. The Global Change Research Act (GCRA) of 1990¹ charged the U.S. Global Change Research Program (USGCRP) with a legal mandate to conduct a scientific assessment on the effects of global change not less frequently than every four years; the third and most recent National Climate Assessment (NCA) was released in May 2014.²

NCA Goal and Vision

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

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

Legislative Foundations

U.S. Global Change Research Program

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

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

National Climate Assessment

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

Institutional Foundations

U.S. Global Change Research Program

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

Department of Agriculture (USDA)

Department of Commerce (DOC)

Department of Defense (DOD)

Department of Energy (DOE)

Department of Health and
Human Services (HHS)

Department of the Interior (DOI)

Department of State (DOS)

Department of Transportation (DOT)

Environmental Protection Agency (EPA)

National Aeronautics and Space Administration (NASA)

National Science Foundation (NSF)

The Smithsonian Institution (SI)

U.S. Agency for International
Development (USAID)

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

National Climate Assessment Components

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



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

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

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

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

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

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

selected from experts nominated during a public open call by the NCA4 SC.

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

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

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

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

The **NCA Technical Support Unit (TSU)** is funded by NOAA and is located at NOAA's National Centers for Environmental Information in Asheville, North Carolina; its

professional staff supports the Assessment's climate science findings, data management and web design, graphics and publications, editing, and other production activities.

NCA4 Authorship Models

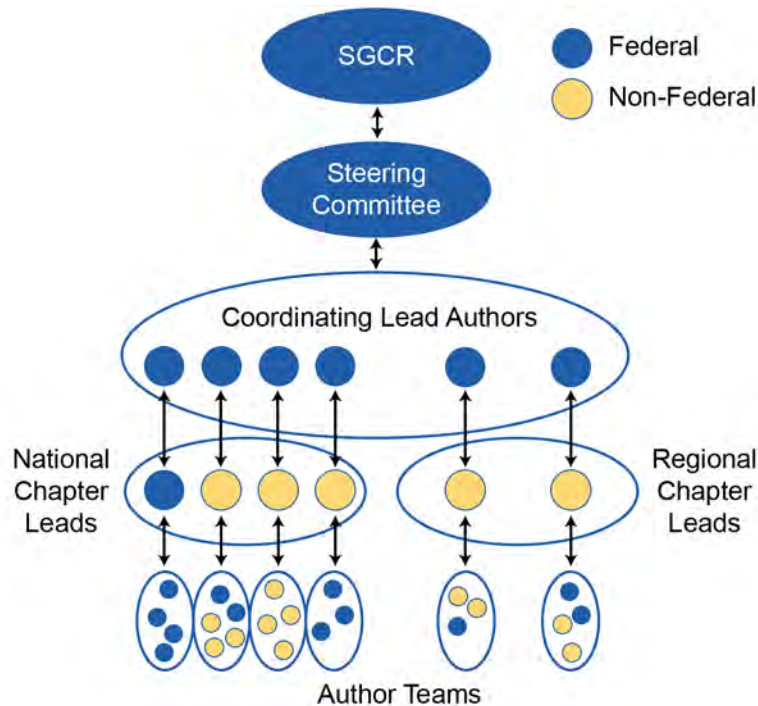


Figure A1.2: In consultation with the Subcommittee on Global Change Research (SGCR), the NCA4 Federal Steering Committee (NCA4 SC) selected Coordinating Lead Authors (CLAs) for each chapter of the NCA. CLAs worked one-on-one with either National or Regional Chapter Leads (CLs), who in turn directed Chapter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

Organization of the National Climate Assessment Participants

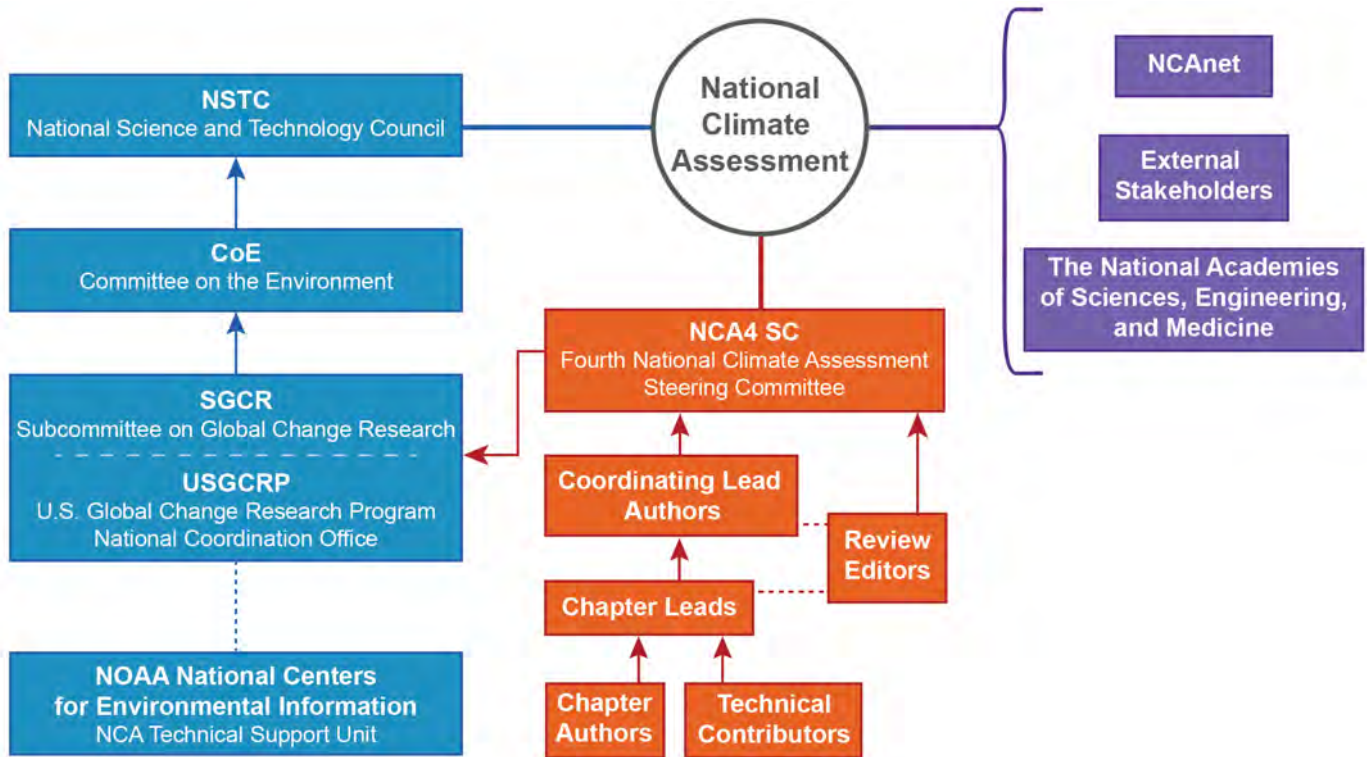


Figure A1.3: Participants in the NCA process can be divided into three broad categories: 1) federal agencies and offices, including the USGCRP (blue boxes); 2) external partners and relevant stakeholders (purple boxes); and 3) NCA4 contributors, including the Federal Steering Committee and report authors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

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

Creating the Fourth NCA Report

Process Development

In May 2015, a Federal Register Notice⁸ requested information to help inform the structure and content of USGCRP's sustained National Climate Assessment process, which NCA4 is a part of. In early 2016, the SGR Principals designated the NCA4 SC to lead NCA4 development, and the NCA4 SC began its work, building on prior work from the Interagency National Climate Assessment (INCA) Working Group, the NCADAC, experiences of TSU and NCO staff, and feedback from the aforementioned public call for information (Figure A1.4).

In July 2016, a Federal Register Notice⁹ was published, seeking input on the draft outline for NCA4. Subsequently, a Federal Register Notice¹⁰ was published in late August 2016,

serving as both a call for regional Chapter Leads and other authors (open call for 30 days) and a call for technical inputs (this part of the call was open for a longer time period, until mid-January 2017).

Concurrent with these public calls for nominations and technical inputs, the NCA4 SC, NCO staff, and TSU staff developed guidance documents for use during the development

of NCA4, ranging from chapter and Traceable Accounts templates to style guides and a literature resource database. Risk-based framing was integrated into the chapter templates and other drafting guidance. Authors had access throughout the process to scientific resources and writing guidance materials on a password-protected Resources website, hosted by the TSU, that also served as a collaboration space for authors.

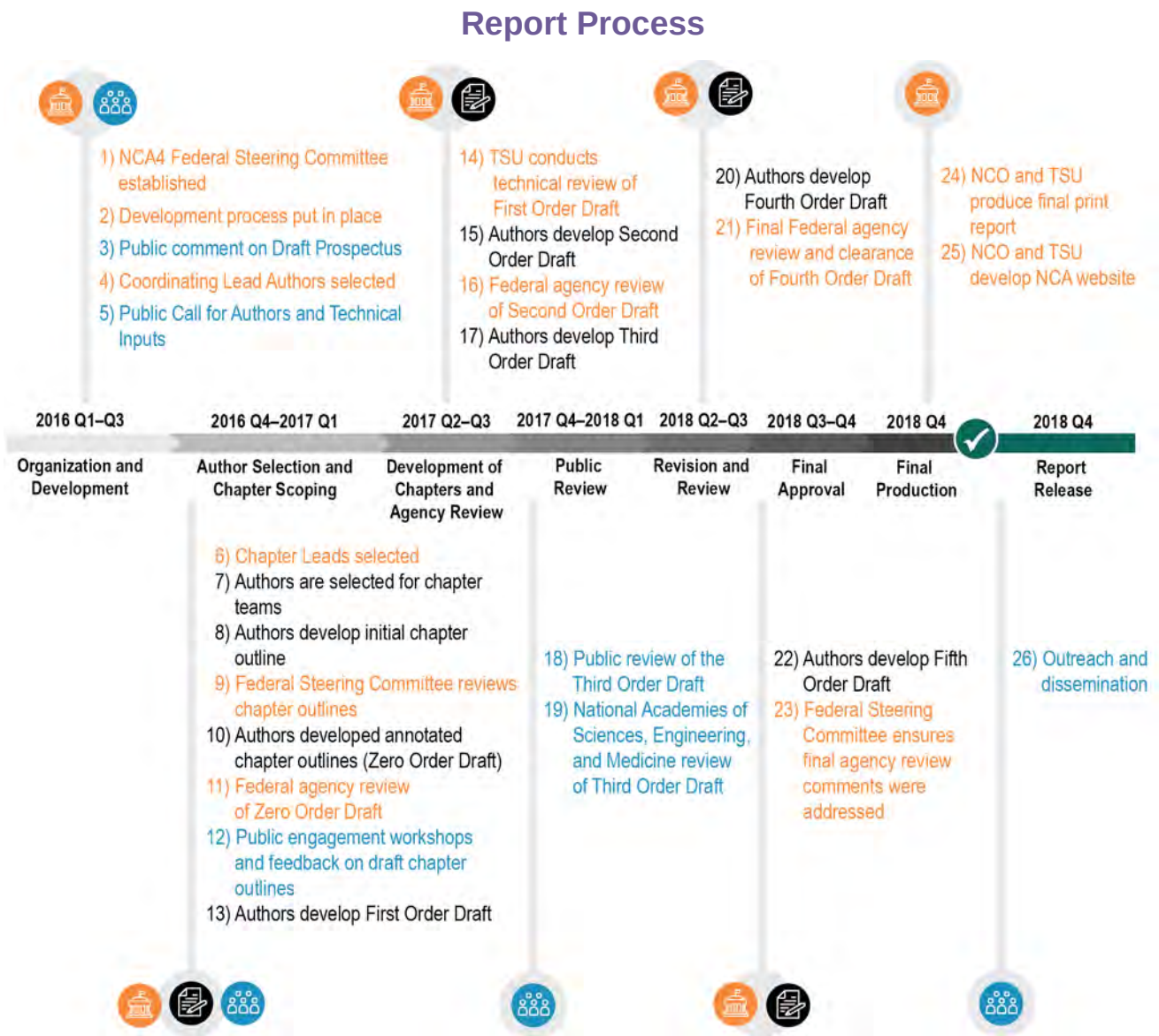


Figure A1.4: This is a graphic illustration of the NCA4 development process. Multiple points of federal review and decision (orange icons) were present throughout the process. In addition, public engagement (blue icons) was a cornerstone of the NCA development process. Authors used these feedback mechanisms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

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

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

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

Initial Chapter Outlines (December 2016 – January 2017)

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

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

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

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

Regional Engagement Around NCA4

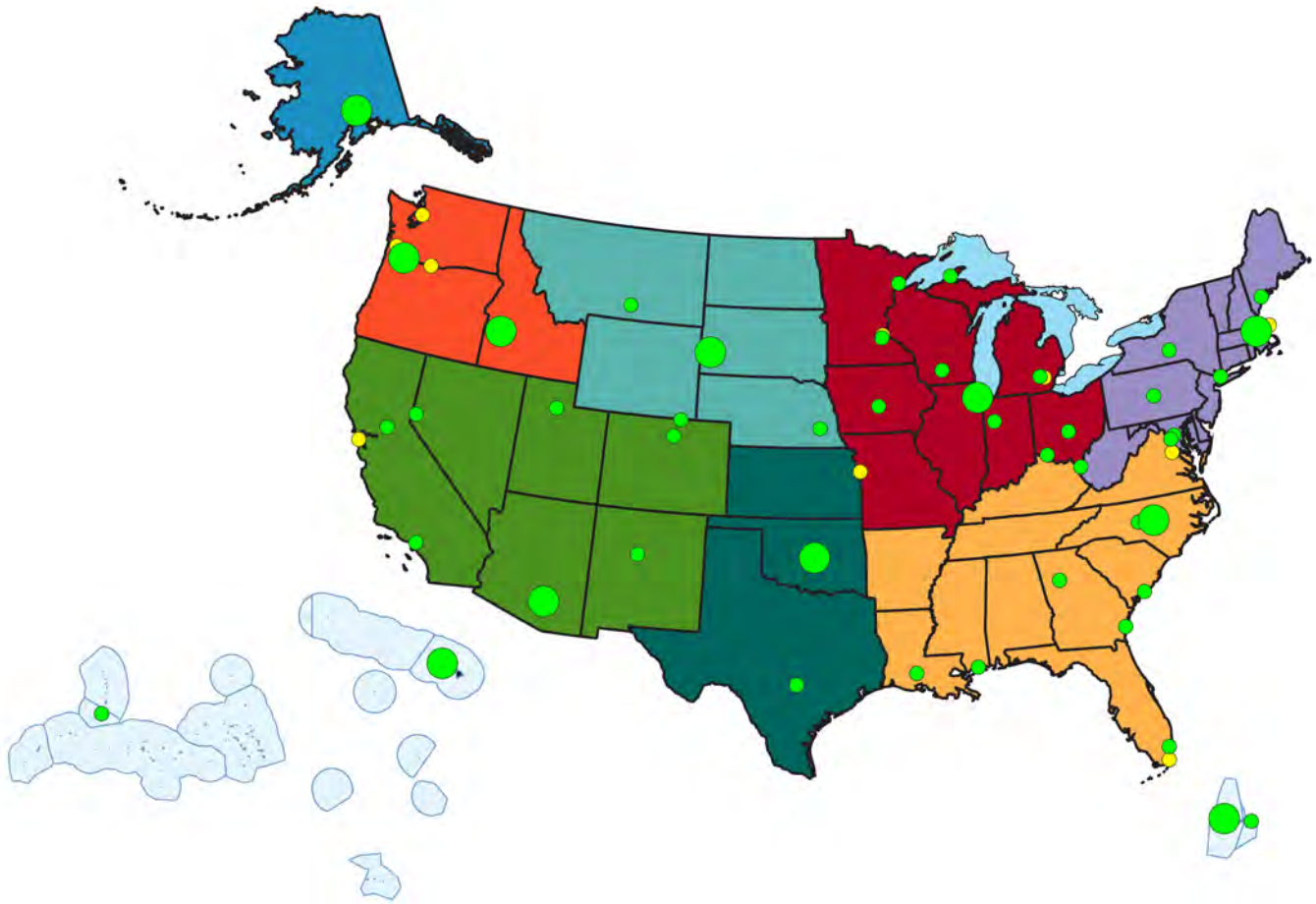


Figure A1.5: The large green dots illustrate the hub locations for the 11 Regional Engagement Workshops held across the country in February to March of 2017. The small green dots indicate satellite locations for those workshops, and the small yellow dots show the locations of some additional engagement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

Regional Engagement Workshops



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

First Chapter Leadership Meeting (CLA-CL1)

On April 4–5, 2017, chapter leadership (CLAs and CLs) convened in Washington, DC, to work on cross-chapter coordination and to discuss additional guidance on chapter drafting, especially on Key Message and Traceable Account formulation. A particularly successful component of this

two-day meeting was an extended “speed-dating” session, where CLAs and CLs from a given chapter would meet with their counterparts from another chapter for 30 minutes to discuss how crosscutting issues would be addressed in their respective chapters to ensure consistent, non-duplicative coverage of key issues.

First Chapter Leadership Meeting



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

Author Training and Drafting

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

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

- Available scenarios products and how to use them
- The EPA's Climate Change Impacts and Risk Analysis (CIRA) project¹¹
- Lessons learned through previous assessments
- Key Message and Traceable Account development
- A walkthrough of the website for scenario products¹²
- Available regional- and local-scale climate variables, through the Localized Constructed Analogs (LOCA) system (see App. 3: Data & Scenarios for more information)
- Metadata requirements and the Global Change Information System (GCIS)
- Climate change indicators

- A report from the National Academies of Sciences, Engineering, and Medicine (NASEM) on *Characterizing Risk in Climate Assessments*¹³
- Risk-based framing
- *Climate Change and Indigenous Peoples: A Synthesis of Current Impacts and Experiences* report¹⁴
- NCA4 Volume I: *Climate Science Special Report* (CSSR)
- NOAA's State Climate Summaries¹⁶
- External, expert peer-review of the draft report by an ad hoc panel of NASEM¹⁷

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

Cross-Chapter Coordination

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

Specific author teams employed many other techniques. For example, the regional authors working on tribal and Indigenous topics began having regular phone meetings in the winter of 2017 and then began meeting with the authors of the national-level "Tribes and Indigenous Peoples" chapter to discuss consistent terminology and language framing around these topics. Authors of another national-scale

chapter (Ch. 10: Ag & Rural) set up phone calls with authors from each of the regional chapters to ensure appropriate coverage of topical issues throughout the regions and to facilitate the roll-up of regional issues related to agriculture and rural communities to the higher-level synthesis chapter.

Review Editor Selection and Role

The NCA4 Federal Steering Committee selected Review Editors (REs) from a slate of candidates nominated through a public open call in the summer of 2017.¹⁸ For their assigned chapter(s), REs ensured that all substantive comments submitted during the Public Comment Period and via an expert review panel of NASEM were appropriately addressed and documented. REs advised CLs on how to handle contentious issues and ensured that significant scientific uncertainties were reflected adequately in the text of NCA4. REs did not provide additional comments on assigned draft chapters but instead focused on the materials derived from the Public Comment Period and NASEM review. REs ensured that each and every comment had been considered by the author team and that the “annotation” (the written response to the comment) was responsive to the comment and indicated any revision made to the chapter(s), including the scientific or logical rationale for said action. REs helped the CLs ensure that the response to each review comment matched the final text of the revised, post-public/NASEM review draft.

All-Author Meeting

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

Review Processes

To begin the writing process, author teams were instructed to develop high-level chapter outlines late in 2016 in light of comments received on the draft prospectus⁹ and guidance provided to authors. The NCA4 Federal Steering Committee reviewed and provided comments on these high-level chapter outlines, which resulted in annotated outlines (Zero Order Drafts) provided to the SGCR for interagency review in January 2017. Comments from this interagency review, alongside input from the suite of public engagement events held throughout the spring of 2017, informed the development of a full First Order Draft.

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

All-Author Meeting



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

Chapter author teams amended the TOD in response to these public and NASEM comments; they were required to respond to each and every comment. Review Editors evaluated the adequacy of the responses to the comments on each chapter. The public

comments and the chapter authors' responses to those comments are available online with the final report (<https://nca2018.globalchange.gov/downloads/>).

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

NCA Final Report

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

Resources Available for Authors

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

Technical Inputs

A public call for technical inputs¹⁰ resulted in the submission of more than 400 peer-reviewed journal articles, reports, and other contributions authored by hundreds of individuals from academia, industry, various levels of government, and nongovernmental organizations. Alongside this public set of technical inputs, the USGCRP NCO conducted a survey of high-impact scientific journals and other peer-reviewed sources to develop a searchable-by-chapter database of over 1,200 articles

and reports for NCA4 authors to consider in their assessment.

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

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

Special Assessment Reports

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

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

The *Second State of the Carbon Cycle (SOC-CR2)*²² was released in December 2018 and provides an update on carbon cycle science across North America that informs several NCA4 chapters.

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

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

The *Third National Climate Assessment (NCA3)* was released in 2014 and covered many of the

same sectors and geographical regions of the United States, providing a foundation for the sectors and regions in NCA4.² NCA4 includes several new national topic chapters and regions as a result of feedback from the public for such information.

Engagement Activities

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

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

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

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

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

NCAnet Activities

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

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

Regional Engagement Workshops and Subsequent Author Meetings

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

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

- U.S. Caribbean Regional Engagement Workshop, Hub: San Juan, Puerto Rico, with one satellite location, March 2017
- Southeast Regional Engagement Workshop, Hub: Raleigh, North Carolina, with seven satellite locations, March 2017
- Northwest Regional Engagement Workshop, Hubs: Portland, Oregon, and Boise, Idaho, March 2017
- Alaska Center for Climate Assessment and Policy Webinar, February 2017
- Association for the Sciences of Limnology and Oceanography, March 2017, Honolulu, Hawai'i
- National Adaptation Forum, May 2017, St. Paul, Minnesota

Listening Sessions

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

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

Presentations

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

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

- National Council for Science and the Environment Annual Meeting, January 2017, Crystal City, Virginia
- American Association for the Advancement of Science Annual Meeting, February 2017, Boston, Massachusetts
- 2017 Joint NACP Ameriflux Principal Investigators Meeting, March 2017, North Bethesda, Maryland
- Southeast & Caribbean Climate Community of Practice 2017 Meeting, April 2017, Charleston, South Carolina
- Association of State Floodplain Managers Annual Conference, May 2017, Kansas City, Missouri
- National Adaptation Forum, May 2017, St. Paul, Minnesota
- Conference of Mayors Annual Meeting, June 2017, Miami Beach, Florida
- Ecological Society of America Annual Meeting, August 2017, Austin, Texas
- American Chemical Society National Meeting, August 2017, Washington, DC
- Pacific Northwest Climate Conference, October 2017, Tacoma, Washington
- Geological Society of America Annual Meeting, October 2017, Seattle, Washington
- Guest lecture at Boston University, November 2017 (virtual)
- American Geophysical Union Fall Meeting, December 2017, New Orleans, Louisiana
- American Meteorological Society Annual Meeting, January 2018, Austin, Texas
- National Council for Science and the Environment Annual Meeting, January 2018, Crystal City, Virginia
- Guest lecture at San Francisco State University, February 2018 (virtual)
- National Association of Regulatory Utility Commissioners Winter Policy Summit, February 2018, Washington, DC
- Air and Waste Management Association webinar, February 2018 (virtual)
- American Association for the Advancement of Science Annual Meeting, February 2018, Austin, Texas
- Center for Climate and Energy Solutions Business Environmental Leadership Council Spring Meeting, March 2018, Washington, DC
- Guest lecture at University of Illinois, April 2018 (virtual)
- Guest lecture at University of Arizona, April 2018 (virtual)
- Electric Power Research Institute (EPRI) Energy 7 Climate Research Seminar, May 2018, Washington, DC
- Adaptation Futures Conference, June 2018, Cape Town, South Africa
- American Association of State Climatologists Annual Meeting, June 2018, Nebraska City, Nebraska

- National Academies of Sciences, Engineering, and Medicine Committee to Advise USGCRP, July 2018, Washington, DC
- Ecological Society of America Annual Meeting, August 2018, New Orleans, Louisiana
- National Academies of Sciences, Engineering, and Medicine Workshop on Subnational Climate Assessments, August 2018, Washington, DC
- Great Lakes Adaptation Forum, September 2018, Ann Arbor, Michigan
- Sigma Xi Annual Meeting, October 2018, Burlingame, California
- American Geophysical Union Fall Meeting, December 2018, Washington, DC

Sustained Assessment: Past, Present, and Future

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

NCA4 was developed within a sustained assessment framework and process, drawing on these previous efforts, as well as an evaluation of the NCA3 process.⁶ As part of this sustained assessment process, NCA4 built on and utilized products, indicators, and tools developed since NCA3 (many of which are described in detail in App. 3: Data & Scenarios). In addition,

in response to gaps identified in NCA3, NCA4 is placed in a broader international context (detailed in the new chapter “Climate Effects on U.S. International Interests” and in the new appendix “Looking Abroad: How Other Nations Approach a National Climate Assessment”). The Climate Change Impacts and Risk Analysis (CIRA) project responds to a recommendation for additional work on quantifying the economic impacts of climate change across sectors of the American economy.¹¹ The CIRA report’s project leaders not only provided information tailored to each NCA4 region and most sectors but also worked with many individual chapters through webinars, conference calls, and other collaborative interactions. Guidance on uncertainty and confidence treatment was also provided early on to NCA4 authors, responding to another sustained assessment recommendation.

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

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

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

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

Acknowledgments

Federal Coordinating Lead Author

David Reidmiller

U.S. Global Change Research Program

Lead Author

Christopher W. Avery

U.S. Global Change Research Program

Contributing Authors

Therese (Tess) S. Carter

U.S. Global Change Research Program

Katie Reeves

U.S. Global Change Research Program

Kristin Lewis

U.S. Global Change Research Program

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Appendix 2. Information in the Fourth National Climate Assessment

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

Identification of Literature Sources

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

The vast majority of sources used in this report are from peer-reviewed scientific literature. A library of relevant and significant peer-reviewed scientific literature was developed through a survey of scientific journals and through submissions collected via a Federal Register Notice (FRN). The FRN, published by the U.S. Department of Commerce on behalf of USGCRP on August 31, 2016, called for the public to submit “recent, relevant scientific and/or technical research studies including observed, modeled

and/or projected climate science information that have been peer-reviewed and published or accepted for publication in scientific journals and/or government reports.”³ In addition, the FRN called for submission of information outside the scientific peer-reviewed literature, such as reports produced by nonprofit communities, but it noted that all information used in the report would need to comply with the IQA.

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

Compliance with the Information Quality Act

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

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

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

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

Acknowledgments

Federal Coordinating Lead Author

David Reidmiller

U.S. Global Change Research Program

Lead Author

Kristin Lewis

U.S. Global Change Research Program

Contributing Author

Christopher W. Avery

U.S. Global Change Research Program

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Appendix 3. Data Tools and Scenario Products

Introduction

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

Tools Within the Sustained Assessment Process

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

of the state of knowledge and establishing rigorous ways of documenting and responding to changes over time.

Scenario Products

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

Overview

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

Selection of Representative Concentration Pathways

NCA4 authors have grounded their assessment in an analysis of the widely used scenarios termed “Representative Concentration Pathways,” or RCPs, that form the foundation for the majority of recent coordinated global climate model experiments. (RCPs are also discussed in this report’s Front Matter.)

Consistent with previous NCAs, NCA4 relies in part on climate scenarios and modeling efforts generated for the Intergovernmental Panel on Climate Change (IPCC) assessments. In May 2015, USGCRP released a memo outlining the decisions regarding climate-related scenarios and the rationale around them.² Specifically, USGCRP decided to use the RCPs^{3,4} and associated model results from the Climate Model Intercomparison Project Phase 5 (CMIP5)⁵ that underpinned the IPCC 5th Assessment Report (AR5), completed in 2013–2014.

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

USGCRP further decided that NCA4 would focus primarily on RCP8.5 and RCP4.5 for framing purposes, while also considering other scenario information where appropriate (for example, RCP2.6). These RCPs capture a range of plausible atmospheric concentration futures that drive climate models. RCP8.5 is the high-end scenario (high emissions, high

concentrations, large temperature increase) in the IPCC’s AR5; it likewise serves as the high-end scenario for NCA4, similar to the use of IPCC’s 4th Assessment Report (AR4) Special Report on Emissions Scenarios (SRES) A2 scenario in NCA3.⁶ RCP4.5 is not the lowest scenario in AR5, but it is similar to the AR4 SRES low-end B1 scenario that was used in NCA3. RCP2.6 represents the low end of the range considered by AR5, but it also assumes significantly greater emissions reductions, even for current and near-term emissions, than previous low-end scenarios used by the IPCC. The range represented by RCP8.5 and RCP4.5, therefore, provides the most continuity and consistency with the IPCC scenarios used for framing purposes by the previous NCA3.

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

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

team;⁴ for illustration, some of the assumptions in those modeling runs include the following:

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

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

scenario range allows for an assessment of impacts at a variety of temperature thresholds.

Products

Overview

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

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

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

To better assist the author teams in meeting their needs, and to reduce the potentially large volume of underlying scenario products from which the authors could potentially draw, NCA4 authors were encouraged to think of the

scenario products as being grouped into the following three USGCRP scenarios: “Lower,” “Higher,” and “Upper Bound” departures from current conditions (Table A3.1).

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

Similarly, the authors were asked to consider how future trends in other critical, non-climatic stressors, including population growth and land-use change, may interact with climate change to exacerbate (or alleviate) climate-related risks. Authors have, therefore, been provided with scenarios of these additional

drivers, grouped with the climate-related scenarios under the Lower, Higher, and Upper Bound USGCRP scenarios (see Ch. 17: Complex Systems for additional discussion on how non-climatic stressors can exacerbate climate-related risks).

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

USGCRP Scenarios

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

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

Downscaled Climate Information

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

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

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

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

Sea Level Rise Scenarios

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

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

Global Mean Sea Level Rise Scenarios

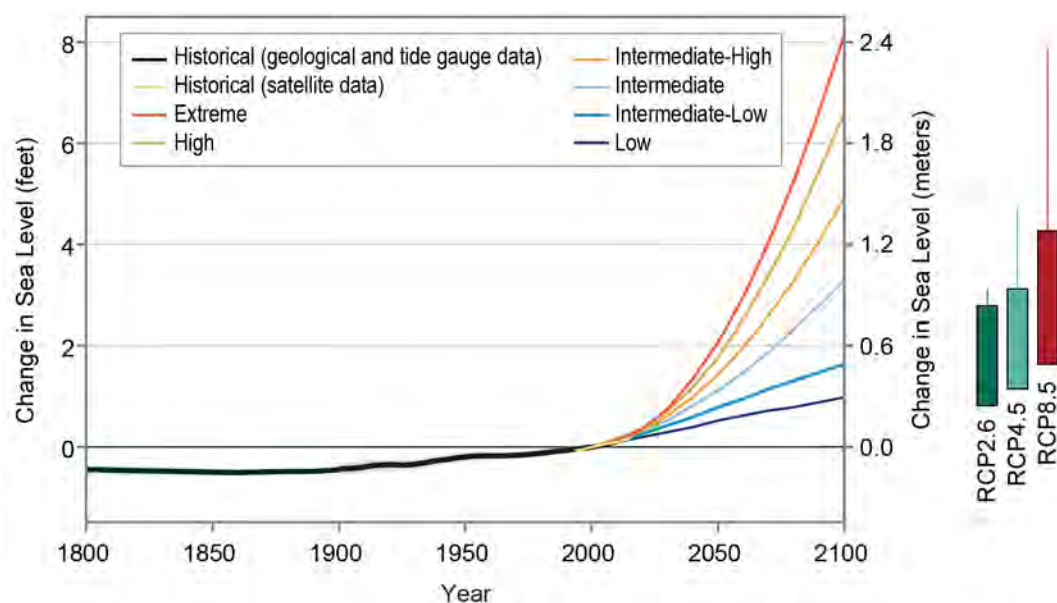


Figure A3.1: The figure shows observed (black and orange lines) and projected changes in global mean (average) sea level rise for 1800–2100. The projected changes are from six global average sea level scenarios developed for an interagency technical report.⁹ The boxes on the right show the *very likely* ranges in sea level rise by 2100 (relative to 2000) corresponding to the three different RCP scenarios. The lines above the boxes show possible increases based on the newest research of the potential contribution to sea level rise from Antarctic ice melt. Source: Ch. 2: Climate, Figure 2.3, adapted from Sweet et al. 2017.⁹ This figure was revised in June 2019. See Errata for details: <https://nca2018.globalchange.gov/downloads>

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

compaction, and groundwater and fossil fuel withdrawals.

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

Population and Land-Use Scenarios

Population and land-use scenarios for NCA4 have been developed through the U.S. Environmental Protection Agency's (EPA) Integrated Climate and Land Use Scenarios (ICLUS) effort. ICLUS explores future changes in human population and developed land use for the contiguous United States. These projections are broadly consistent with peer-reviewed storylines of population growth and economic development that are now widely used by the climate change impacts community.¹⁰ Specifically, the different population and land-use change scenarios stem from global population and urbanization assumptions underlying two

different future trajectories from the Shared Socioeconomic Pathways (SSPs) effort:¹¹ SSP2, which represents a business-as-usual trajectory, similar to the U.S. Census population projection (out to 2060), and SSP5, which represents a trajectory with higher fertility and higher net migration into the United States.¹² At the global scale, socioeconomic assumptions under SSP2 are broadly consistent with the concentration pathway and resultant radiative forcing for RCP4.5, whereas the socioeconomic assumptions under SSP5 are more consistent with RCP8.5.

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

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

Indicators

Overview

The USGCRP hosts an interagency climate-related indicator platform at <http://www.globalchange.gov/browse/indicators>. Climate indicators for this purpose are defined as observations or other measures that are used to track the state of or the trend in conditions with a scientifically based relationship to the changing climate. For example, businesses might look at

the unemployment index as one of a number of indicators representing the condition of the economy. Similarly, indicators related to climate—which may be physical, ecological, or societal—can be used to understand how environmental conditions are changing, to assess risks and vulnerabilities, and to help inform resilience and planning for climate impacts.

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

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

USGCRP Indicators

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

- annual GHG index
- arctic glacial mass balance

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

Additional Indicator Resources

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

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

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

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

Other relevant sources of indicator information include

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

Climate Change Indicators

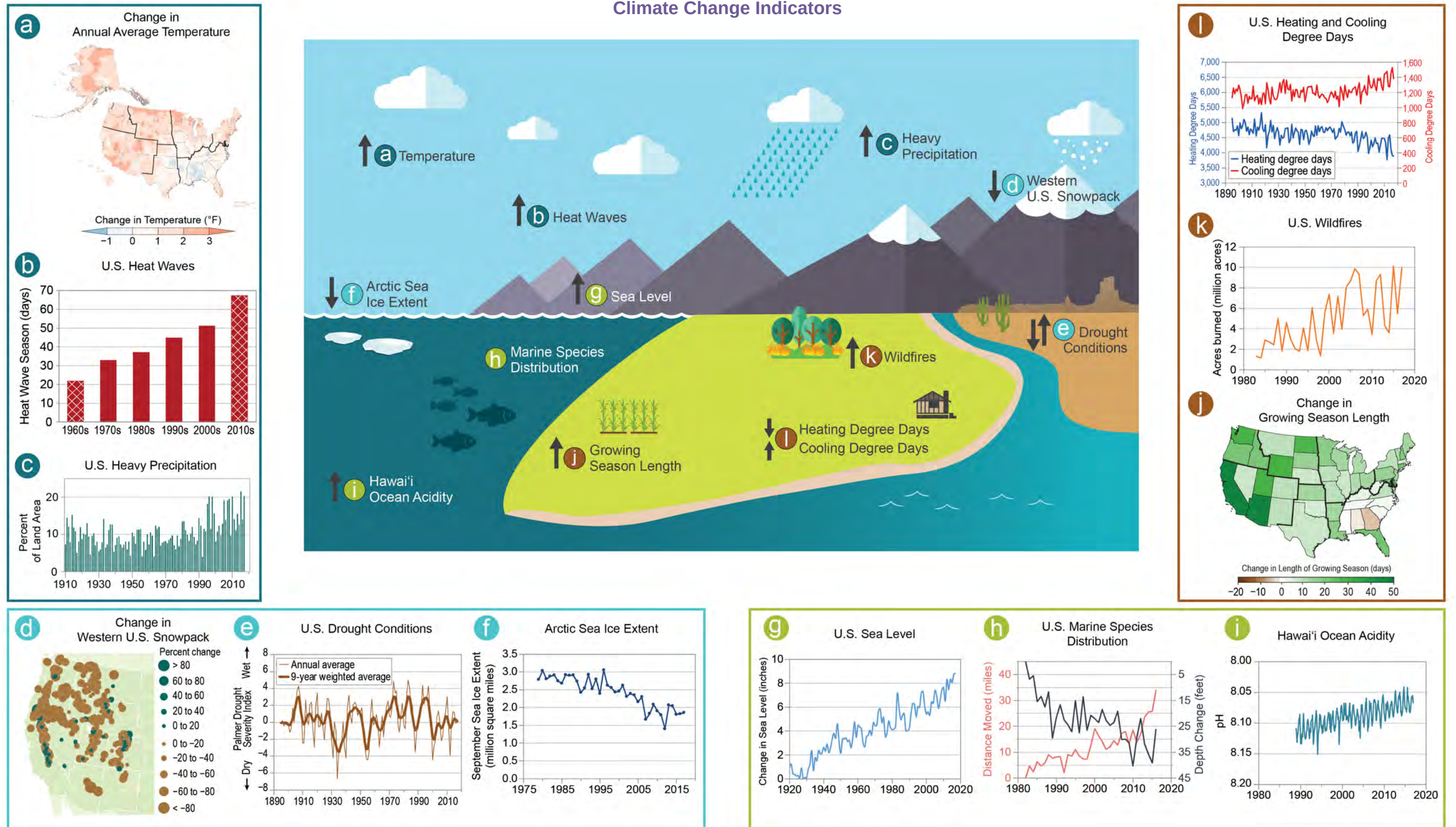


Figure A3.2: Long-term observations demonstrate the warming trend in the climate system and the effects of increasing atmospheric greenhouse gas concentrations (Ch. 2: Climate, Box 2.2). This figure shows climate-relevant indicators of change based on data collected across the United States. Upward-pointing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

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

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

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

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

Climate Resilience Toolkit

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

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

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

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

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

Steps to Resilience

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

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

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

To help users answer these questions, the Toolkit offers plain language narratives—excerpted from the NCAs and other authoritative sources—that summarize ways that U.S. sectors, regions, and built and natural environments are vulnerable to, and have been impacted by, climate and non-climate stressors. These narratives are cross-linked with over 110 real-world case studies, from across

the United States and its territories, highlighting people in communities and businesses who have successfully taken action to manage their climate risks. Additionally, the site’s narratives and case studies are cross-linked with science-based decision support tools to illustrate how people have used those tools to plan and build resilience.

CRT Tools and the Climate Explorer

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

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

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

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

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

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

Climate Resilience Toolkit Case Study Categories

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

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

Climate Resilience Toolkit Decision Support Tools

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

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

Global Change Information System

Summary

The National Climate Assessment and Development Advisory Committee (NCADAC), which guided the development of NCA3, recommended in 2013 that the NCA process “manage data to maximize utility and transparency.”¹⁹

The report also highlighted the importance of “developing a comprehensive web-based system to deploy and manage global change information and present it in a way that can be used by and benefit scientists, the public, and decision-makers.” To achieve these goals, the USGCRP established the Global Change Information System (GCIS).

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

Identifiers

Each item (for example, a report, dataset, or organization) referenced in the GCIS has a unique, persistent identifier. When possible,

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

Provenance and Semantics

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

Traceability and Provenance in GCIS

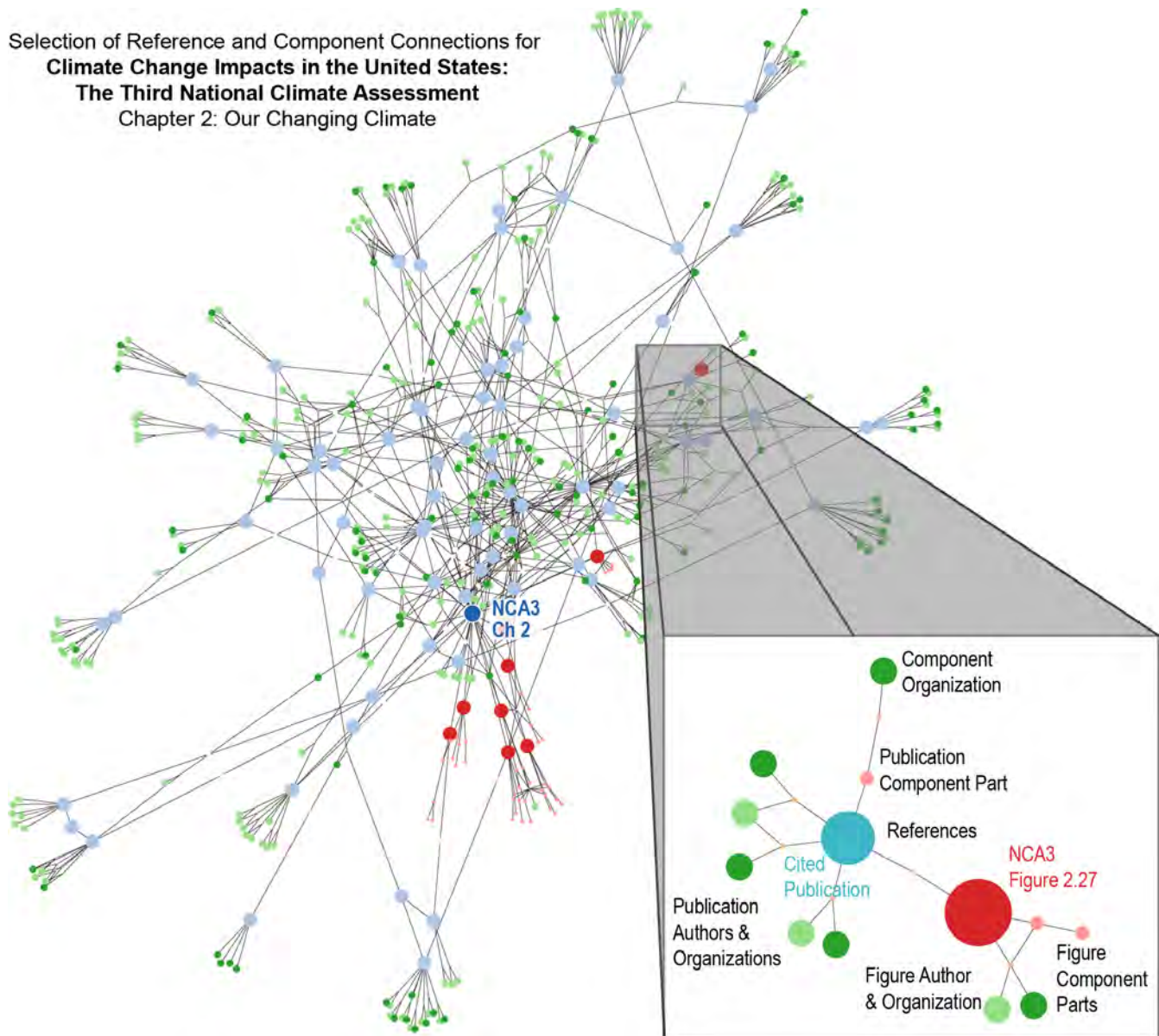


Figure A3.3: This figure is a graphic representation of traceability and provenance within the Global Change Information System (GCIS). All records within GCIS seek to have each component of this chain tracked and available to any reader. Tracking each of these components allows for any interested member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

NOAA State Climate Summaries

Overview

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

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

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

Historical Climate

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

Future Scenarios

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

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Federal Coordinating Lead Author

David Reidmiller

U.S. Global Change Research Program

Lead Author

Christopher W. Avery

U.S. Global Change Research Program/ICF

Reid Sherman

U.S. Global Change Research Program/Straughan
Environmental

Contributing Authors

Michael Kolian

U.S. Environmental Protection Agency

William V. Sweet

National Oceanic and Atmospheric Administration

Kenneth E. Kunkel

North Carolina State University

Kathryn Tipton

U.S. Global Change Research Program/ICF

David Herring

National Oceanic and Atmospheric Administration

Christopher Weaver

U.S. Environmental Protection Agency

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

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

Introduction

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

The approach taken in this appendix has been to select a small set of assessment models from geographically varied nations with diverse capacities to conduct such assessments. Information on the assessment mandates and requirements, process, content structure, and international dimensions are included for each assessment. Because this appendix is intended to be illustrative rather than comprehensive, it does not summarize every report produced internationally—including, for example, the most recent climate assessment produced by the European Union.¹

Selected National Climate Assessments



Figure A4.1: The U.S. National Climate Assessment represents one model for conducting national climate assessments, but there are many other national assessment models from countries around the world. Table A4.1 highlights key attributes for each national assessment model chosen for inclusion in this appendix, namely the assessment model type, a link to the assessment website, and the number of assessments to date (and the years they were completed). Source: USGCRP.

This appendix, one of several new additions to the NCA, was made in response to gaps identified in previous NCAs, as well as public input during the NCA4 scoping process—namely, to integrate the international context across NCA4 and, specifically, to include how NCA4 relates to complementary international assessment efforts. Therefore, in addition to this appendix, NCA4 includes a new national-level topic chapter focusing on U.S. international

interests (see Ch. 16: International). The Hawai'i & U.S.-Affiliated Pacific Islands and (new) U.S. Caribbean regional chapters are intended to provide an entry point for Small Island Developing States (SIDS) to consider similarities in the risks they face and inform adaptation efforts within their own borders. Moreover, numerous case studies embedded throughout the report examine transboundary and international trade and economic issues.

Table A4.1: Summary of Assessment Models by Country

Nation(s)	Assessment Model	Number of Assessments to Date
Brazil	Not mandated by law, developed by a scientific panel established by ministerial ordinance, and modeled after IPCC assessment reports. http://www.pbmc.coppe.ufrj.br/en/	1 assessment (2013)
Canada	Not mandated by law, developed by federal government departments and modeled after the NCA4. http://www.nrcan.gc.ca/environment/impacts-adaptation/10029	6 assessments (1998, 2008 [2], 2014, 2016, 2017)
India	Not mandated by law, developed by domestic research institutions established by ministerial ordinance. http://www.moef.nic.in/division/indian-network-climate-change-assessment	1 assessment (2010)
Liberia	Not mandated by law, developed with U.S. support to fill knowledge gaps resulting from intra-national conflict. https://www.researchgate.net/publication/237102310_liberia_climate_change_assessment	1 assessment (2013)
Mongolia	Not mandated by law, developed by ministerial climate change office. http://www.jcm-mongolia.com/wp-content/uploads/2015/11/MARCC-Final-Bk-2014-book-lst.9.17-ilovepdf-compressed.pdf	2 assessments (2009, 2014)
Pacific Islands	Not mandated by law, developed as a collaborative regional-scale assessment between Australian agencies and Pacific countries. https://www.pacificclimatechangescience.org/publications/reports/	1 assessment (2011)
Saudi Arabia	Not mandated by law, voluntarily developed by national government as part of UNFCCC reporting requirements. http://www.cdmdna.gov.sa/report/40/third-national-communication-of-the-kingdom-of-saudi-arabia	3 assessments (2005, 2011, 2016)
Singapore	Not mandated by law, commissioned by government, and developed by a mixed team of national and international partners. http://ccrs.weather.gov.sg/Publications-Second-National-Climate-Change-Study-Science-Reports/	1 assessment (2015)
United Kingdom	Mandated by law, developed by a statutory independent committee. https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/uk-climate-change-risk-assessment-2017/	2 assessments (2012, 2017)

Federative Republic of Brazil^{2,3}

Overview

Brazil released a National Assessment Report on Climate Change (RAN1) in 2013. The report was produced by a national scientific panel established by the government and was modeled on the Assessment Reports produced by the Intergovernmental Panel on Climate Change (IPCC). The RAN1 describes observed and projected impacts, assesses vulnerabilities in different national sectors and regions, and identifies options for adaptation measures. The report is intended to inform the development of the country's national planning activities related to climate change.

Assessment Mandate and Objectives

While Brazil does not have a nationally mandated climate assessment, the government has recognized the need for a national scientific body capable of providing policymakers at the federal, state, and local levels with objective information on the environmental, social, and economic effects of climate change. To this end, the Brazilian Panel on Climate Change (PBMC) was created in 2009 by a joint ordinance of the Ministry of the Environment and the Ministry of Science, Technology, Innovation and Communication.

The structure of the PBMC is based on the IPCC and includes a Steering Committee, Scientific Committee, Executive Secretariat, Working Groups, and Technical Support Units. The Panel is responsible for creating a range of policy-relevant products, including National Assessment Reports that provide a comprehensive scientific assessment of climate changes relevant to Brazil, Special Reports focusing on specific topics, and Technical Reports to help develop methods for monitoring and evaluating Brazil's greenhouse gas emissions. The PBMC represents the first national effort to consolidate and organize existing knowledge on climate change in Brazil onto a single platform.

The Panel's report is intended to support the development and implementation of public policies such as the National Plan on Climate Change, Sectoral Mitigation and Adaptation Plans to Climate Change, and the National Adaptation Plan. As of October 2017, the RAN1 was the only national assessment report published by the Panel.

Assessment Process

Under the supervision of the PBMC's Steering Committee, the RAN1 report was written by approximately 100 scientists drawn from national research institutions and distributed across the Panel's three Working Groups (WGs), each of which composed a separate volume for the report. The Panel's Scientific Committee, composed of the coordinators of the WGs, developed the scope of each WG volume, coordinated the drafting of the report, and provided guidance to authors and reviewers throughout the process. The Panel's Steering Committee selected the authors through a public call, approved the Scientific Committee's proposed scoping for the report, approved the various drafts, and provided general direction for the Panel's work. At the end of the process, a Summary for Policy Makers was approved by the PBMC Plenary, which included the Steering and Scientific Committees' memberships, as well as representatives from federal and state governments. In the RAN1, the PBMC made use of the work of a range of observational and modeling research programs that have recently been developed in Brazil at the national and state levels.

Assessment Content Structure

The RAN1 report consists of three separate volumes, each of which is produced by one of the PBMC's three WGs and matches the structure of the IPCC Assessment Reports: Volume 1: The Scientific Basis of Climate Change; Volume 2: Impacts, Vulnerability and Adaptation; Volume 3: Mitigation of Climate

Change. Volume 1 surveys the current state of the scientific knowledge of climate change in Brazil and South America. Volume 2 evaluates the projected climate impacts and vulnerabilities across a range of natural systems, in five national regions (Northern, Northeast, Southern, Southeast, Center-West), and in key societal sectors (Rural and Urban communities, Energy, Industry, and Transportation). A topic receiving special focus is the impact of climate change on human health, well-being, and safety. Each volume was originally drafted in Portuguese but also has an accompanying Executive Summary in English.

International Dimensions

The RAN1 report does not explicitly consider the international dimensions of the impacts of climate change on Brazil. Some findings of the assessment were, however, incorporated into Brazil's 2016 National Communication, which it shared with the international community as part of its United Nations Framework Convention on Climate Change (UNFCCC) reporting requirements. The work of the PBMC is also intended to support international cooperation among developing countries and help countries build their capacity to respond to climate change through the sharing of assessment methodologies, the knowledge gained from these assessments, and Brazil's own national experiences with climate change. This is part of the PBMC's efforts to advance greater South-South dissemination and capacity building. The PBMC also received support from the British Government's Department for International Development.

Canada⁴

Overview

The government of Canada has completed six national-scale science assessments of climate change impacts and adaptation since 1998. Each assessment has included regional and/or sectoral analysis. Led by federal government

departments, these assessments involved multiyear, collaborative processes that engaged academia, all levels of government, industry associations, Indigenous organizations, and the private sector. The current assessment process was launched in 2017 and will be completed in 2021.

Assessment Mandate and Objectives

National assessment products, rather than being nationally mandated, are deliverables of government programs supported through specific federal budget cycles. Assessment processes focus on the development and dissemination of products that synthesize and provide value-added analysis of the current state of knowledge. Assessments build awareness of the issues; inform research priorities, policy responses, and adaptation strategies; and enhance capacity to undertake adaptation. These goals are achieved through an inclusive, scientifically rigorous assessment process and the resulting reports.

Assessment Process

The lead federal department (currently, Natural Resources Canada) works with contributing departments to coordinate the assessment process and provide other secretariat functions. A multi-stakeholder advisory committee oversees the process and provides guidance and input throughout, from scoping to post-release. Subject matter experts are engaged as lead and contributing authors, while expertise in areas such as information technology and technical editing is contracted, as required. In addition, each assessment process includes extensive peer review to ensure accuracy and relevance. New elements of the current assessment process include a greater focus on communications, increased engagement of a broad range of Canadians, and the development of a suite of products that will be released over the assessment cycle, rather than just one large volume at the end.

Assessment Content Structure

Canadian assessments focus on climate change impacts and adaptation and draw from all relevant existing sources of knowledge (peer-reviewed publications, gray literature, Indigenous knowledge, and practitioner experience). Climate trends and projections for Canada are included to establish a robust, national overview of current and future changes in physical climate, in the context of informing the impacts and adaptation discussions. Since assessment activities are not legislated, there is flexibility in determining the content and structure, and these decisions take user needs into account. Past assessments have taken either a regional approach—addressing all major regions of Canada or a specific sensitive region (for example, marine coasts)—or a sectoral approach, focusing on a specific sector (for example, health or transportation) or multiple sectors within one volume. Increased engagement, interest, and resources have allowed the current assessment process to expand to include both regional and sectoral volumes, as well as stand-alone reports on climate trends and projections (led by Environment and Climate Change Canada) and on health issues (led by Health Canada).

International Dimensions

The 2008 assessment⁵ included a chapter titled “Canada in an International Context.” This chapter examined how climate change impacts on other countries, and their adaptation responses, could affect Canada. Sections focused on continental effects (North America), the surrounding oceans, and global impacts. The chapter also discussed Canada’s international obligations on adaptation. The 2021 assessment will include a chapter on international dimensions that addresses transboundary issues, trade and supply chains, and linkages between adaptation, sustainable development, and disaster risk reduction globally.

Republic of India⁶

Overview

In 2010, India produced an assessment focused on a combined regional and sectoral analysis of climate change impacts through 2030. While not mandated by law, the federal government called for the assessment to be produced by domestic research institutions. The report represents the nation’s first attempt to produce its own comprehensive climate impacts assessment and provides an integrated assessment of four primary regions and four primary sectors of key economic importance to the country. It focuses on observed and projected impacts and potential adaptation measures.

Assessment Mandate and Objectives

While India does not have a nationally mandated climate assessment, the government has stated the need for a comprehensive framework for assessing national- and state-level climate impacts, drawing from domestic technical and policy expertise. In 2009, the Ministry of Environment and Forests established the Indian Network for Climate Change Assessment (INCCA) to conduct research on climate drivers and impacts, prepare assessments of national vulnerability and adaptation, develop decision-support systems, and build capacity for the management of climate risks and opportunities. The broad purpose of the INCCA is to build an independent national research capacity for understanding and responding to climate change and to reduce dependence on external assessments and information sources.

Assessment Process

The INCCA brings together 125 research institutions and more than 250 scientists from across the country. The 2010 assessment report was prepared by 43 researchers from 18 separate institutions, led by the Ministry of Environment and Forests (now the Ministry of Environment, Forest and Climate Change). The Ministry also organized a series

of consultative meetings in 2009 and 2010 to inform the report's development. For the analysis of current and projected climate risks, the report utilized both historical observations and high-resolution climate projections using modeling tools obtained from the United Kingdom's Hadley Centre for Climate Prediction and Research.

Assessment Content Structure

The INCCA 2010 report is organized as a “4×4” assessment model that explores the impacts of climate change through the 2030s focused on four key climate-dependent sectors of the Indian economy (Agriculture, Water, Natural Ecosystems and Biodiversity, and Human Health) in four climate-sensitive regions (the Himalayan region, the Western Ghats, the Coastal Area, and the North-East region). The report provides an introduction to the INCCA framework, a discussion of regional climate observations and projections, an assessment of each sector and region, and an assessment of research needs moving forward.

International Dimensions

The INCCA 2010 report does not explicitly consider the international dimensions of the impacts of climate change on India. The findings of the assessment were, however, subsequently updated and incorporated into India's 2012 National Communication, which India shared with the international community through the UNFCCC. The reports were also produced using financial and technical support from international partners.

In January 2015, the United States and India created the Partnership for Climate Resilience. This Partnership aims to strengthen scientific cooperation on climate research and improve information available to decision-makers, building on the 2010 climate change assessment. Experts from the National Oceanic and Atmospheric Administration and academia,

with support from the State Department, have partnered with Indian scientific experts and institutions to develop downscaled data for the Indian subcontinent at higher resolution than was previously available and to improve the capacity of local decision-makers to understand, predict, and plan for current and future impacts of climate variability and change.

Republic of Liberia⁷

Overview

In 2013, the U.S. Agency for International Development (USAID) Mission in Liberia commissioned the Republic of Liberia's Climate Change Assessment with involvement from the Liberian government. This international support provided Liberia with additional capacity to advance climate science data to the benefit of Liberian decision-makers. The assessment focused on potential climate change impacts on key Liberian natural resources and used refined downscaled modeling to produce data more targeted to the needs of Liberian decision-makers.

Assessment Mandate and Objectives

In March 2013, the Liberia USAID Mission produced Liberia's Climate Change Assessment to analyze natural resource vulnerabilities with respect to USAID climate change programs in the country. A key motivation for the report was to fill the knowledge gap caused by the loss of climate and environmental information during the country's civil wars. Its objectives were, broadly speaking, twofold: 1) assess the vulnerabilities of natural systems, and 2) provide a knowledge base to promote national climate resilience and improve the condition of rural subsistence farming communities.

Assessment Process

Although this assessment was not nationally mandated or produced by the national government, several Liberian agencies were engaged in developing the assessment in partnership

with U.S. federal agencies. It was prepared by the U.S. Department of Agriculture's Forest Service International Programs and reviewed by USAID. To achieve its objectives, the Liberia USAID Mission, in collaboration with the U.S. Forest Service, tasked a multidisciplinary team from the Forest Service Southern Research Station with conducting a climate change assessment. The team briefed Liberian agencies and civil society on the results. It also provided USAID and the Environmental Protection Agency of the Republic of Liberia with the modeled climate data and targeted training on how they might use the data.

Assessment Content Structure

The report focuses on the potential impacts of climate change on agriculture, fisheries, forests, energy, and mining. The assessment also touches on social vulnerability and the capacity of key segments of the Liberian population to adapt to current and projected climate change. It also examines the impacts on society from policy responses to climate change.

International Dimensions

This assessment was launched and largely conducted by an external international entity, namely USAID, though the Liberian government was involved in the process. The climate projections also utilized modeling tools and data obtained from the international community.

Mongolia⁸

Overview

The government of Mongolia has produced two Mongolia Assessment Reports on Climate Change (MARCC), in 2009 and 2014. The assessments are intended to serve as a definitive source of information on the latest research on climate change as it relates to Mongolia. This includes observed and projected climate changes; impacts on environmental, economic, and social sectors; and information

on societal responses to climate change. The findings and recommendations of the MARCC reports are intended to feed into the country's national development programs and climate action plans.

Assessment Mandate and Objectives

While there is no explicit legal mandate for the MARCC, it does exist within an evolving national legal and policy framework to address climate challenges and meet Mongolia's obligations under international agreements on the environment and climate change. Under the country's revised Law on Air (2012), the Ministry of Environment and Tourism manages a Climate Change Coordination Office (CCCO), which implements Mongolia's commitments to the UNFCCC and integrates climate change issues into other national sectors. In addition, a National Action Programme on Climate Change (NAPCC), approved by Parliament in 2011, defines strategic objectives and outlines specific activities to integrate climate change concerns into national development plans and action plans. The MARCC 2014 report is intended to support the NAPCC by presenting the most current knowledge of observed and projected climate change. It does so by describing climate impacts on human and natural systems, highlighting strategies and technology needs for mitigation/adaptation measures, presenting a national greenhouse gas (GHG) inventory, and explaining the policy framework for climate action in Mongolia. The report is designed for use by a wide audience: government officials, policy- and decision-makers, members of professional societies and scientific communities, educators and students, and the general public.

Assessment Process

The MARCC 2014 report was prepared under the supervision of the chair of the CCCO, with logistical and technical support from CCCO staff. Financial support for preparation and

publication of the report was provided by the German development agency GIZ (German Corporation for International Cooperation) on behalf of the German Federal Ministry for Economic Cooperation and Development. Subject matter experts wrote each chapter. The document was originally drafted in Mongolian and then translated into English. In its presentation of current and projected climate change, MARCC 2014 made use of the IPCC's Fifth Assessment Report (AR5).

Assessment Content Structure

The MARCC 2014 report begins with basic information on observed and projected climate change in Mongolia, organized at the national and regional level. Subsequent chapters organize the impacts of climate change sectorally, on a range of natural and human systems. For natural systems, the report focuses on soil and pasture, forest ecosystems, fauna, water resources, natural disasters, land degradation and desertification, and dust/sand storms. For human systems, the report focuses on animal husbandry, agriculture, poverty and human development, infrastructure, and human health. Later chapters review adaptation options and possible mitigation measures, including a national GHG inventory and related technology issues. The final chapter covers policy frameworks, legal instruments, and institutional arrangements.

International Dimensions

While neither the MARCC 2009 nor the MARCC 2014 explicitly considers the international dimensions of climate change impacts on Mongolia, both reports do provide descriptions of the international policy setting within which Mongolia's climate change efforts exist. In particular, the MARCC 2014 describes in detail Mongolia's recent engagement with a range of international organizations to develop its domestic climate change policy and related interventions, in general. In addition, both the

2009 and 2014 MARCC reports were produced with financial and technical support from international partners.

Pacific Islands⁹

Overview

The Australian government published a Climate Change in the Pacific (CCP) report in 2011. The regional-level report provides a peer-reviewed scientific assessment of how the climate of the western Pacific region is changing. The report was produced through a collaboration between Australian government agencies and Pacific countries. It reviews current trends and projections of climate change for 14 Small Island Developing States (SIDS) and Timor-Leste, and identifies research and knowledge gaps in the region.

Assessment Mandate and Objectives

The significant research gaps identified in the IPCC's Fourth Assessment Report (AR4) served as the foundation for the creation of Australia's Pacific Climate Change Science Program (PCCSP). The objectives of the program are to conduct comprehensive climate change science, build capacity in partner countries across the Pacific to undertake scientific research, and disseminate information to partner countries' stakeholders and other parties. As part of Australia's five-year International Climate Change Adaptation Initiative, the PCCSP produced the Climate Change in the Pacific report in 2011. The report is intended to help countries in the Pacific prioritize adaptation measures, assess their vulnerability, develop adaptation strategies, and address research gaps described in the IPCC's AR4.

Assessment Process

The PCCSP is a collaborative research partnership among Australian government agencies, 14 Pacific Island countries, and Timor-Leste, as well as regional and international organizations. The 14 Pacific countries are the Cook

Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Sāmoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. To ensure that research is of relevance to partner country decision-makers, coordinated information sharing, capacity building, and engagement have been conducted throughout all research areas and among all partner countries.

Assessment Content Structure

This report contains two volumes. The first provides a detailed assessment and analysis of changes in the observed and projected climate of the PCCSP region. The second includes climate change reports for each partner country. Each of the 15 reports includes sections on seasonal cycles, climate variability, observed annual trends, and projections for atmospheric and oceanic variables.

International Dimensions

Climate Change in the Pacific is a regional scientific assessment supported by the government of Australia that involves collaboration with multiple countries, both within the Pacific region and beyond it through the contributions of international organizations.

Kingdom of Saudi Arabia¹⁰

Overview

The government of the Kingdom of Saudi Arabia (KSA) has voluntarily produced three assessments of the nation's vulnerability to climate change. The most recent national vulnerability assessment was completed in 2016 and incorporated into the National Communication submitted by the KSA to satisfy its UNFCCC reporting requirements. The vulnerability assessments identify current and future climate-related impacts as well as potential adaptation measures in specific sectors. They also identify knowledge gaps to be addressed by future assessments.

Assessment Mandate and Objectives

While the KSA does not have a nationally mandated climate assessment, it is required, as part of its reporting obligations and commitments under the UNFCCC (Article 12 and subsequent decisions taken at Conferences of the Parties), to submit National Communications that provide certain information related to its greenhouse gas (GHG) emissions and the implementation of actions to address climate change. These reports provide the international community with a recent inventory of each Party's GHG emissions, a description of the policy initiatives that the country has taken to respond to and prepare for climate change, and any other information relevant to the implementation of its commitments under the UNFCCC. As part of this reporting, the KSA has included a national climate assessment in all of its National Communications, submitted in 2005, 2011, and 2016. These assessments analyze regional climate trends and projections and their impacts on a range of nationally important sectors.

Assessment Process

The KSA's most recent National Communication was produced by a Designated National Authority, in coordination with a team of academics, consultants, and other experts drawn from relevant government ministries, research institutions, and other organizations. In particular, the General Authority of Meteorology and Environmental Protection (the Kingdom's environmental agency) and the Ministry of Energy, Industry and Mineral Resources played important roles in its development. The report was produced with assistance from the national oil and gas company (Saudi Aramco), the United Nations Environment Programme, and the Global Environment Facility. For the analysis of current and projected climate risks, the report utilized historical observations and high-resolution climate projections using modeling tools obtained from the United

Kingdom's Hadley Centre for Climate Prediction and Research.

Assessment Content Structure

Within the KSA's Third National Communication, the climate assessment component includes a chapter focusing on climate science, describing baseline conditions, recent trends, and future climate scenarios, as well as the methodologies employed and climate model outputs. Subsequent sectoral chapters describe vulnerabilities and identify national adaptation measures covering the areas of water resources, desertification, agriculture and food security, and human health. Each of these chapters offers more detailed and technical discussion of the sectoral impacts as well as recommendations for future research to address information and data gaps.

International Dimensions

The KSA's National Communications have not explicitly considered the international dimensions of climate change impacts on the country. The reports reflect the country's ongoing engagement with the UNFCCC process for assessing climate-related risks and developing policies to address them. The reports were also produced using financial and technical support from international partners.

Republic of Singapore¹¹

Overview

The Republic of Singapore's National Climate Change Studies are voluntary reports, commissioned by the government and produced by a mixed team of national and international partners. Singapore has undertaken two studies, the first of which was completed in 2015 and the second of which is currently underway and will include a vulnerability analysis.

Assessment Mandate and Objectives

The National Environment Agency of Singapore (NEA) commissioned the current National

Climate Change Study in recognition of the island nation's increasing vulnerability to climate change. The purpose is to assess the current and projected impacts from climate change, focusing on variables of greatest importance to the country (temperature, precipitation, and sea level), and to assess the vulnerability of various sectors to a changing climate. The results of the study will feed into the next stage of Singapore's national adaptation planning efforts.

Assessment Process

The NEA leads the development of the study, which is divided into two phases. Phase 1, which was published in 2015, provided long-term climate projections, while Phase 2, currently under development, will assess the vulnerability of Singapore's population, environment, and infrastructure to a changing climate. The work on Phase 1 was performed jointly by experts from the Centre for Climate Research Singapore and the Met Office Hadley Centre in the United Kingdom, with contributions from partners at the Australian Commonwealth Scientific and Industrial Research Organisation and the United Kingdom's National Oceanography Centre–Liverpool. The focus of the Phase 1 study was to produce high-resolution regional climate and sea level projections that extend to 2100. To ensure that outcomes from the study would be of use to decision-makers, stakeholder engagement was integrated early on in the process, with representatives from a range of national agencies taking part. In particular, engagement activities involved stakeholders' focusing on six thematic clusters: coastal protection; water resources and drainage; public health; network infrastructure; building, structure, and town infrastructure; and biodiversity and greenery.

Assessment Content Structure

The Phase 1 report of Singapore's Second National Climate Change Study is made up

of 10 primary chapters, each focusing on a specific element of the modeling process that generated the high-resolution projections to be used in the vulnerability assessment. The report also includes detailed technical appendices and supplementary information.

International Dimensions

Phase 1 of the current study was completed in close partnership with the United Kingdom and Australia. Additionally, the foundation for its scientific assessment stemmed from work conducted by the IPCC. The completed study will not explicitly consider international effects.

United Kingdom¹²

Overview

The government of the United Kingdom (UK) is legally required to produce a Climate Change Risk Assessment (CCRA) every five years and then develop National Adaptation Programmes to address those risks and build resilience to climate change. The core component of the CCRA is an independently produced Evidence Report that assesses climate risks and impacts in the UK. The Evidence Report feeds into a high-level Synthesis Report that identifies key areas of climate risk to be prioritized for action. The government evaluates this Synthesis Report and produces its final Risk Assessment, which is presented to Parliament. The most recent Evidence Report was developed using a risk-based framing and explicitly considers the international dimensions of climate impacts to the UK.

Assessment Mandate and Objectives

The 2008 Climate Change Act requires the UK government to present a CCRA to Parliament every five years. The purpose of the assessment is to evaluate the risks that current and predicted climate change impacts pose to the UK and, ultimately, to guide the development of National Adaptation Programmes

for the UK and its component countries (the administrations of England, Northern Ireland, Scotland, and Wales).

Assessment Process

Under the 2008 Climate Change Act, two CCRAs have been completed, one in 2012 and the most recent in 2017. The Act establishes an independent body, the Committee on Climate Change, whose Adaptation Sub-Committee (ASC) was responsible for the CCRA Evidence Report and Synthesis Report in 2017. The Evidence Report summarizes the current state of knowledge of climate risks and opportunities in the UK and identifies priority areas needing urgent further action over the next five years. For the most recent Evidence Report, the ASC convened teams of experts to assess a wide range of climate risks and opportunities and assign urgency scores to inform national adaptation planning. The analysis was supplemented by several specially commissioned research studies on specific climate impacts and was informed by engagement with and review by stakeholders inside and outside of the government and across all four UK countries. The Synthesis Report, authored by the ASC, summarizes the Evidence Report and then identifies six areas of risk to be managed as priorities for the next five years. For the most recent CCRA, the government largely approved the conclusions from the various products of the ASC, which it produced in its final UK Climate Change Risk Assessment 2017.

Assessment Content Structure

The most recent Evidence Report includes multiple individual products. The main report is an independent analysis authored by academics, consultants, and other experts in the public and private sectors, as well as civil society organizations throughout the UK. It reviews evidence for current and future climate change in the UK, provides a description of the assessment methodology, and includes

technical chapters focused on specific sectors. Separate national summaries, authored by the ASC, present evidence specific to Scotland, England, Northern Ireland, and Wales.

International Dimensions

The CCRA Evidence Report has expanded since its inception to examine impacts at increasingly wider scales, both across sectors and geographically. While the focus of the first report was on a limited set of direct impacts within the UK, the most recent CCRA also considers the impacts on the UK from international effects, both direct (for example,

through disruption of trade and supply chains) and indirect (for example, through price volatility of imported commodities). These topics are explored in a dedicated international dimensions chapter.

Acknowledgments

Federal Coordinating Lead Author

David Reidmiller

U.S. Global Change Research Program

Lead Author

Katherine Weingartner

U.S. Global Change Research Program/ICF (through September 2017)

Contributing Author

Apurva Dave

U.S. Global Change Research Program/ICF

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Appendix 5. Frequently Asked Questions

This appendix is an update to the frequently asked questions (FAQs) presented in the Third National Climate Assessment (NCA3). New questions based on areas of emerging scientific inquiry are included alongside updated responses to the FAQs from NCA3. The answers are based on the U.S. Global Change Research Program's (USGCRP) sustained assessment products, other peer-reviewed literature, and consultation with experts.

Federal Coordinating Lead Author

David Reidmiller

U.S. Global Change Research Program

Lead Author

Matthew Dzaugis

U.S. Global Change Research Program/ICF

Contributing Authors

Christopher W. Avery

U.S. Global Change Research Program/ICF

Allison Crimmins

U.S. Environmental Protection Agency

LuAnn Dahlman

National Oceanic and Atmospheric Administration

David R. Easterling

NOAA National Centers for Environmental Information

Rachael Gaal

National Oceanic and Atmospheric Administration

Emily Greenhalgh

National Oceanic and Atmospheric Administration

David Herring

National Oceanic and Atmospheric Administration

Kenneth E. Kunkel

North Carolina State University

Rebecca Lindsey

National Oceanic and Atmospheric Administration

Thomas K. Maycock

North Carolina State University

Roberto Molar

National Oceanic and Atmospheric Administration

Brooke C. Stewart

North Carolina State University

Russell S. Vose

NOAA National Centers for Environmental Information

Technical Contributors are listed at the end of the chapter.

Recommended Citation for Chapter

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Introduction to Climate Change

How do we know Earth is warming?

Many indicators show conclusively that Earth has warmed since the 19th century. In addition to warming shown in the observational record of oceanic and atmospheric temperature, other evidence includes melting glaciers and continental ice sheets, rising global sea level, a longer frost-free season, changes in temperature extremes, and increases in atmospheric humidity, all consistent with long-term warming.

Observations of surface temperature taken over Earth's land and ocean surfaces since the 19th century show a clear warming trend. Temperature observations have been taken consistently since the 1880s or earlier at thousands of observing sites around the world. Additionally, instruments on ships, buoys, and floats together provide a more-than-100-year record of sea surface temperature showing that the top 6,500 feet of Earth's ocean is warming in all basins.¹ These observations are consistent with readings from satellite instruments that measure atmospheric and sea surface temperatures from space. Used together, land-, ocean-, and space-based temperature observations show clear evidence of warming at Earth's surface over climatological timescales (<http://www.globalchange.gov/browse/indicators> for more indicators of change) (see also Ch. 2: Climate).

Scientists around the world have been measuring the extent and volume of ice contained in the same glaciers every few years since 1980. These measurements show that, globally, there is a large net volume loss in glacial ice since the 1980s. However, the rate of the ice loss varies by region, and in some cases yearly glacier advances are observed (see FAQ “How does climate change affect mountain glaciers?”). Ice sheets on Antarctica and Greenland have been losing ice mass consistently since 2002, when advanced satellite measurements of their continental ice mass began (see FAQ “Is Antarctica losing ice? What about Greenland?”). Arctic sea ice coverage has been monitored using satellite imagery since the late 1970s, showing consistent and large declines in September, the time of year when the minimum coverage occurs.²

There are additional observational lines of evidence for warming. For example, the area of land in the Northern Hemisphere covered by snow each spring is now smaller on average than it was in the 1960s.³ Tide gauges and satellites show that global sea level is rising, both as a result of the addition of water to the ocean from melting glaciers and from the expansion of seawater as it warms (Ch. 2: Climate; Ch. 8: Coastal). Lastly, as air warms, its capacity to hold water vapor increases, and measurements show that atmospheric humidity is increasing around the globe, consistent with a warming climate (see Ch. 3: Water; see also Ch. 1: Overview, Figure 1.2 for more indicators of a warming world).

What makes recent climate change different from warming in the past?

Increases in global temperature since the 1950s are unusual for two reasons. First, current changes are primarily the result of human activities rather than natural physical processes. Second, temperature changes are occurring much faster than they did in the past.

Our planet's climate has changed before. Sedimentary rocks and fossils show clear evidence for a series of long cold periods—called ice ages—followed by warm periods. Common archaeological and geological processes for dating past events show that these cycles of cooling and warming occurred about once every 100,000 years for at least the last million years.

Before major land-use changes and industrialization, changes in global temperature were caused by natural factors, including regular changes in Earth's orbit around the sun, volcanic eruptions, and changes in energy from the sun.⁴ Major warming and cooling events were driven by natural variations of Earth's orbit that altered the amount of sunlight reaching Earth's Arctic and Antarctic regions, resulting in the retreat and advance of massive ice sheets. Additionally, quiescent or active periods of volcanic eruptions also could contribute to warming or cooling events, respectively.⁵

Natural factors are still affecting the planet's climate today (see Figure A5.5). Yet since the beginning of the Industrial Revolution, human use of coal, oil, and gas has rapidly changed the composition of the atmosphere (Figure A5.1). Land-use changes (such as deforestation), cement production, and animal production for food have also contributed to the increase in levels of greenhouse gases in the atmosphere. Unlike past changes in climate, today's warming is driven primarily by human activity rather than by natural physical processes (see Figure A5.5) (see also Ch. 2: Climate).

Current warming is also happening much faster than it did in the past. Scientific records from ice cores, tree rings, soil boreholes, and other “natural thermometers”—often called proxy climate data—show that the recent increase in temperature is unusually rapid compared to past changes (see Figures A5.2 and A5.4). After an ice age, Earth typically took thousands of years to warm up again; the observed rate of warming over the last 50 years is about eight times faster than the average rate of warming from a glacial maximum to a warm interglacial period.⁴

Carbon Emissions in the Industrial Age

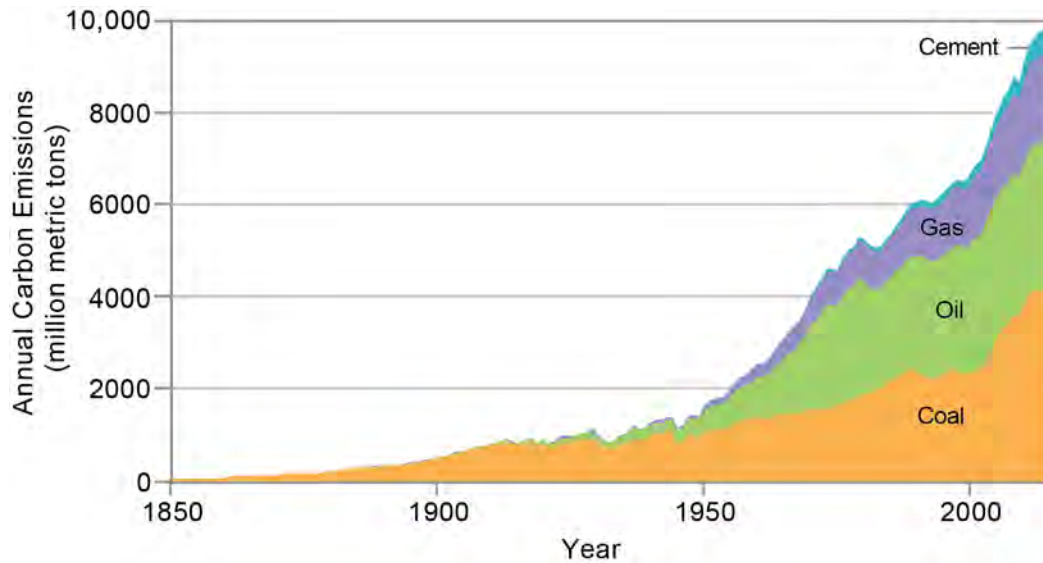


Figure A5.1 Humans have changed the atmosphere by burning coal, oil, and gas for energy and by producing cement. This graph shows the total global carbon emissions from these activities from 1850 to 2009. A range of other human activities, such as cutting down forests and livestock production, account for additional carbon emissions. Source: Walsh et al. 2014.⁶

1,700 Years of Global Temperature Change

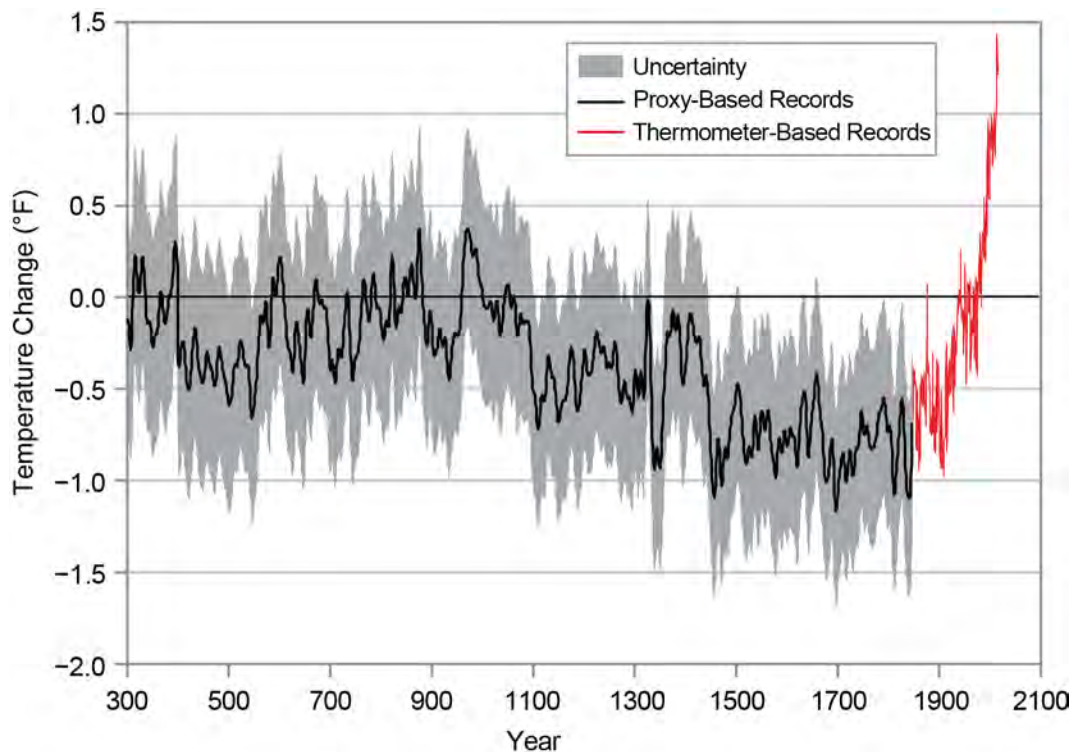


Figure A5.2 Average global temperature has increased rapidly over the last 1,700 years compared to the 1961–1990 average. The red line shows temperature data based on surface observations. The black line shows temperature data from proxies, including data from tree rings, ice cores, corals, and marine sediments. The comparison of proxy- and thermometer-based records suggests that temperatures are now higher than they have been in at least 1,700 years. The steep portion of the graph since about 1950 shows how rapidly temperature has increased compared to previous changes. Source: adapted from Mann et al. 2008.⁷

What's the difference between global warming and climate change?

Though some people use the terms “global warming” and “climate change” interchangeably, their meanings are slightly different. Global warming refers only to Earth’s rising surface temperature, while climate change includes temperature changes and a multitude of effects that result from warming, including melting glaciers, increased humidity, heavier rainstorms, and changes in the patterns of some climate-related extreme events.

By itself, the phrase global warming refers to increases in Earth’s annual average surface temperature. Today, however, when people use the phrase, they usually mean the recent warming that is due in large part to the rapid increase of greenhouse gases (GHGs) in the atmosphere from human activities such as deforestation and the burning of fossil fuels for energy. Thus, “global warming” has become a form of shorthand for a complex scientific process.

The entire globe is not warming uniformly. Some areas may cool (such as the North Atlantic Ocean), while some may warm faster than the global average (such as the Arctic). The term climate change refers to the full range of consequences or impacts that occur as atmospheric levels of GHGs rise and different parts of the earth system respond to a higher average surface temperature. For instance, observed long-term trends, such as increases in the frequency of drought and heavy precipitation events, are not technically warming trends, but they are related to current warming and are processes of climate change (Ch 2: Climate).

Climate Science

What are greenhouse gases, and what is the greenhouse effect?

Greenhouse gases (GHGs) are gases that absorb and emit thermal (heat) infrared radiation. Carbon dioxide, methane, nitrous oxide, ozone, and water vapor are the most prevalent GHGs in Earth's atmosphere. These gases absorb heat emitted by Earth's surface and re-emit that heat into Earth's atmosphere, making it much warmer than it would be otherwise—a process known as the greenhouse effect.

Most of Earth's atmosphere is made up of nitrogen (N_2) and oxygen (O_2), neither of which is considered a greenhouse gas. Other gases, known as greenhouse gases (GHGs), behave very differently from O_2 and N_2 when it comes to infrared radiation emitted from Earth. GHGs, such as water vapor, carbon dioxide (CO_2), and methane (CH_4), have a more complex molecular structure (made up of three or more atoms, as opposed to the symmetrical, two-atom molecules of O_2 and N_2) that absorbs some of the energy emitted from Earth's surface and then re-radiates that energy in all directions, including back down towards the surface. This ultimately traps energy in the lower atmosphere in the form of heat (Figure A5.3). This greenhouse effect makes the average temperature of Earth nearly 60°F warmer than it would be in the absence of these GHGs. Even a tiny amount of these gases can have a huge effect on the amount of heat trapped in the lower atmosphere, just like a tiny amount of anthrax can have a huge effect on human health.

Many GHGs, including CO_2 , CH_4 , water vapor, and nitrous oxide (N_2O), occur naturally in the atmosphere. However, atmospheric concentrations of these GHGs have been rising over the last few centuries as a result of human activities. In addition, human activities have added new, entirely human-made GHGs to the atmosphere, including chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).⁵

As the global population has increased, so have GHG emissions. This in turn makes the greenhouse effect stronger, resulting in higher average temperature around the globe (Ch 2: Climate).

The Greenhouse Effect

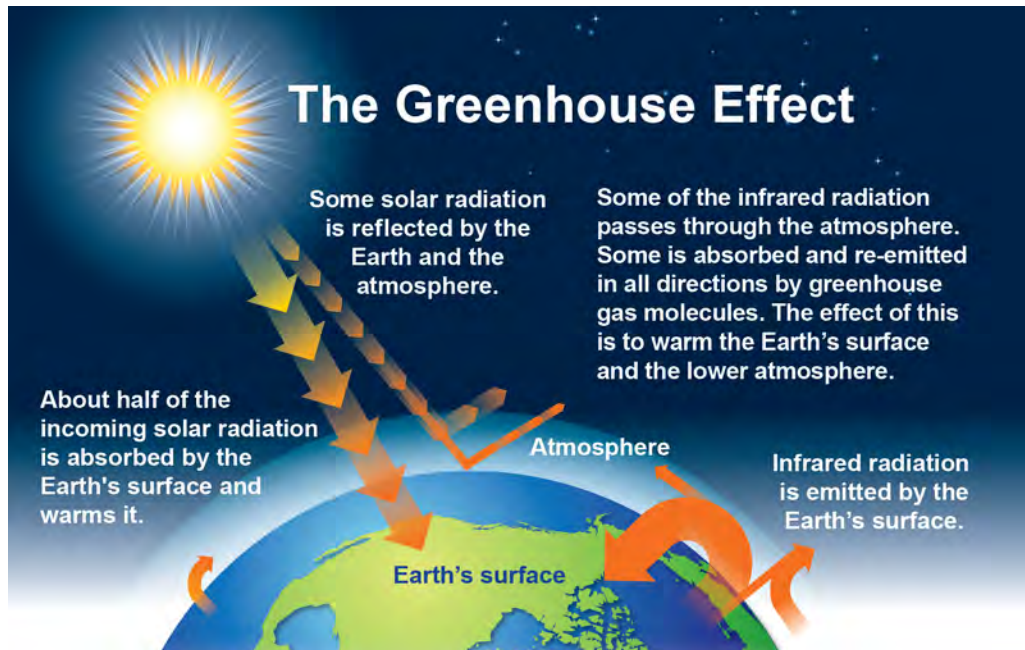


Figure A5.3: The figure shows a simplified representation of the greenhouse effect. About half of the sun's radiation reaches Earth's surface, while the rest is reflected back to space or absorbed by the atmosphere. Naturally occurring greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), do not absorb most of the incoming shortwave (visible) energy from the sun, but they do absorb the longwave (infrared) energy re-radiated from Earth's surface. This energy is then re-emitted in all directions, keeping the surface of the planet much warmer than it would be otherwise. Human activities—predominantly the burning of fossil fuels (coal, oil, and gas)—are increasing levels of CO_2 and other GHGs in the atmosphere, which is amplifying the natural greenhouse effect and thus increasing Earth's temperature. Source: adapted from EPA 2016.⁸

Why are scientists confident that human activities are the primary cause of recent climate change?

Many independent lines of evidence support the finding that human activities are the dominant cause of recent (since 1950) climate change. These lines of evidence include changes seen in the observational records that are consistent with our understanding, based on physics, of how the climate system should change due to human influences. Other evidence comes from climate modeling studies that closely reproduce the observed temperature record.

*The Climate Science Special Report*⁹ concludes, “human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century.” The Earth’s climate only warms or cools significantly in response to changes that affect the balance of incoming and outgoing energy. Over long timescales (tens to hundreds of thousands of years), orbital cycles produce long periods of warming and cooling. Over shorter timescales, two factors could generally force changes in Earth’s temperature to a measurable degree: (1) changes in the amount of energy put out by the sun, and (2) changes in the concentrations of greenhouse gases (GHGs) in Earth’s atmosphere. Recent measurements of the sun’s energy show no trend over the last 50 years. Additionally, observations show that the lower atmosphere (troposphere) has warmed while the upper atmosphere (stratosphere) has cooled. If the observed warming had been due to an increase in energy from the sun, then all layers of Earth’s atmosphere would have warmed, which is not what scientists observe. Thus, we can eliminate changes in the energy received from the sun as a major factor in the warming observed since about 1950.¹⁰

This leaves the possibility that changes in GHG concentrations in the atmosphere are the primary cause of recent warming. Atmospheric carbon dioxide (CO₂) levels have increased from approximately 270 parts per million (ppm) during preindustrial times to the current 408 ppm observed in 2018 (see <https://www.esrl.noaa.gov/gmd/ccgg/trends/>)—levels that exceed any observed over the past 800,000 years (Figure A5.4). In addition, atmospheric concentrations of other GHGs (including methane and nitrous oxide) have increased over the same period. This increase in GHG concentrations has coincided with the observed increase in global temperature. Scientists use methods that provide chemical “fingerprints” of the source of these increased emissions and have shown that the 40% increase in atmospheric CO₂ levels since the Industrial Revolution is due mainly to human activities (primarily the combustion of fossil fuels) and not due to natural carbon cycle processes.⁵

Other evidence attributing human activities as the dominant driver of observed warming comes from climate modeling studies. Computer simulations of Earth’s climate based on historical data of observed changes in natural and human influences accurately reproduce the observed temperature record over the last 120 years. These results show that without human influences, such as the observed increases in GHG emissions, Earth’s surface would have cooled slightly over the past half century. The only way to closely replicate the observed warming is to include both natural and human forcing changes in climate models (Figure A5.5). Thus, the observational record and modeling studies both point to human factors being the main cause for the recent warming (Ch.2: Climate).

800,000 Years of CO₂ and Temperature Change

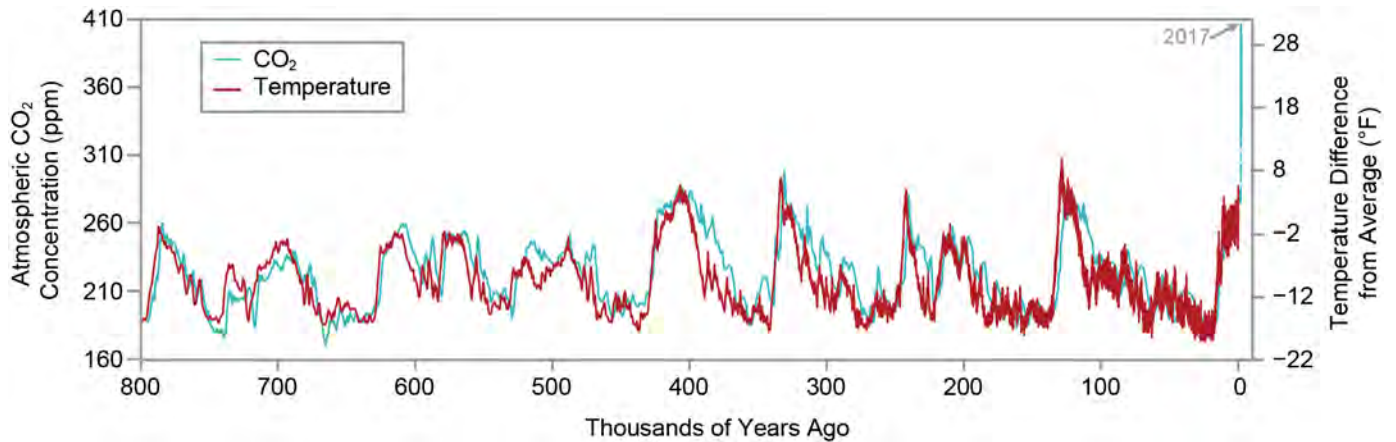


Figure A5.4: This chart shows atmospheric CO₂ concentrations (left axis, blue line) and changes in temperature (compared to the average over the last 1,000 years; right axis, red line) over the past 800,000 years, as recorded in ice cores from Antarctica. Also shown are modern instrumental measurements of CO₂ concentrations through 2017. Current CO₂ concentrations are much higher than any levels observed over the past 800,000 years. Source: adapted from EPA 2017.¹¹

Human and Natural Influences on Global Temperature

Figure A5.5: Both human and natural factors influence Earth's climate, but the long-term global warming trend observed over the past century can only be explained by the effect that human activities have had on the climate.

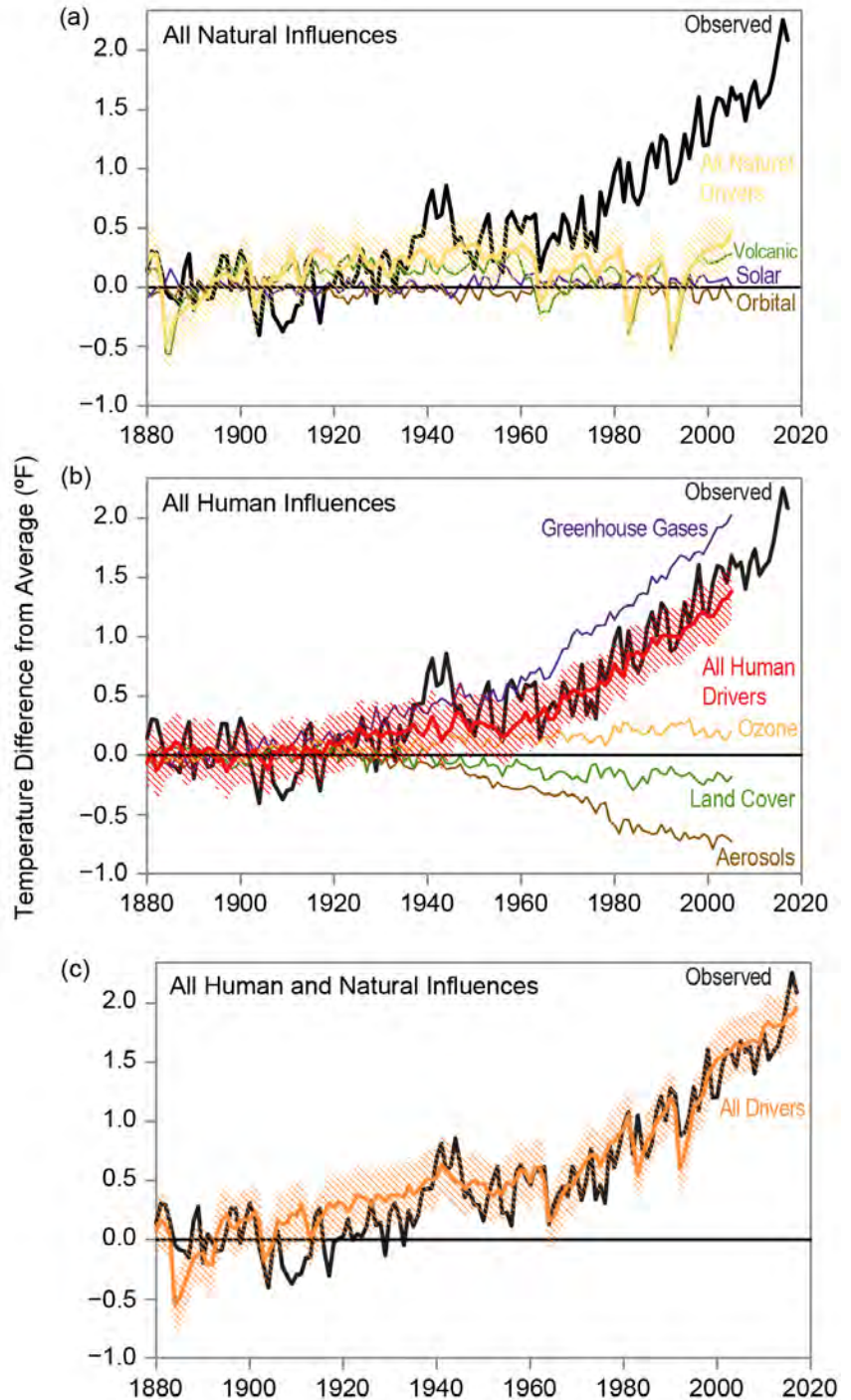
Sophisticated computer models of Earth's climate system allow scientists to explore the effects of both natural and human factors. In all three panels of this figure, the black line shows the observed annual average global surface temperature for 1880–2017 as a difference from the average value for 1880–1910.

The top panel (a) shows the temperature changes simulated by a climate model when only natural factors (yellow line) are considered. The other lines show the individual contributions to the overall effect from observed changes in Earth's orbit (brown line), the amount of incoming energy from the sun (purple line), and changes in emissions from volcanic eruptions (green line). Note that no long-term trend in globally averaged surface temperature over this time period would be expected from natural factors alone.⁴

The middle panel (b) shows the simulated changes in global temperature when considering only human influences (dark red line), including the contributions from emissions of greenhouse gases (purple line) and small particles (referred to as aerosols, brown line) as well as changes in ozone levels (orange line) and changes in land cover, including deforestation (green line). Changes in aerosols and land cover have had a net cooling effect in recent decades, while changes in near-surface ozone levels have had a small warming effect.⁵ These smaller effects are dominated by the large warming influence of greenhouse gases such as carbon dioxide and methane. Note that the net effect of human factors (dark red line) explains most of the long-term warming trend.

The bottom panel (c) shows the temperature change (orange line) simulated by a climate model when both human and natural influences are included. The result matches the observed temperature record closely, particularly since 1950, making the dominant role of human drivers plainly visible.

Researchers do not expect climate models to exactly reproduce the specific timing of actual weather events or short-term climate variations, but they do expect the models to capture how the whole climate system behaves over long periods of time. The simulated temperature lines represent the average values from a large number of simulation runs. The orange hatching represents uncertainty bands based on those simulations. For any given year, 95% of the simulations will lie inside the orange bands. See Chapter 2: Climate for more information. Source: NASA GISS.



What role does water vapor play in climate change?

Water vapor is the most abundant greenhouse gas (GHG) in the atmosphere and plays an important role in Earth's climate, significantly increasing Earth's temperature. However, unlike other GHGs, water vapor can condense and precipitate, so water vapor has a short life span in the atmosphere. Air temperature, and not emissions, controls the amount of water vapor in the lower atmosphere. For this reason, water vapor is considered a feedback agent and not a driver of climate change.

Water vapor is the primary GHG in the atmosphere, and its contribution to Earth's greenhouse effect is about two or three times that of carbon dioxide (CO₂). Human activities directly add water vapor to the atmosphere primarily through increasing evaporation from irrigation, power plant cooling, and combustion of fossil fuels. Other GHGs, such as CO₂, are not condensable at atmospheric temperatures and pressures, so they will continue to build up in the atmosphere as long as their emissions continue.¹²

The amount of water vapor in the lower atmosphere (troposphere) is mainly controlled by the air temperature and proximity to a water source, such as an ocean or large lake, rather than by emissions from human activities. Fluctuations in air temperature change the amount of water vapor that the air can hold, with warmer air capable of holding more moisture. Increases in water vapor levels in the lower atmosphere are considered a “positive feedback” (or self-reinforcing cycle) in the climate system. As increasing concentrations of other GHGs (for example, carbon dioxide, methane, and nitrous oxide) warm the atmosphere, atmospheric water vapor concentrations increase, thereby amplifying the warming effect (Figure A5.6). If atmospheric concentrations of CO₂ and other GHGs decreased, air temperature would drop, decreasing the ability of the atmosphere to hold water vapor, further decreasing temperature.^{5,12}

Water Vapor and the Greenhouse Effect

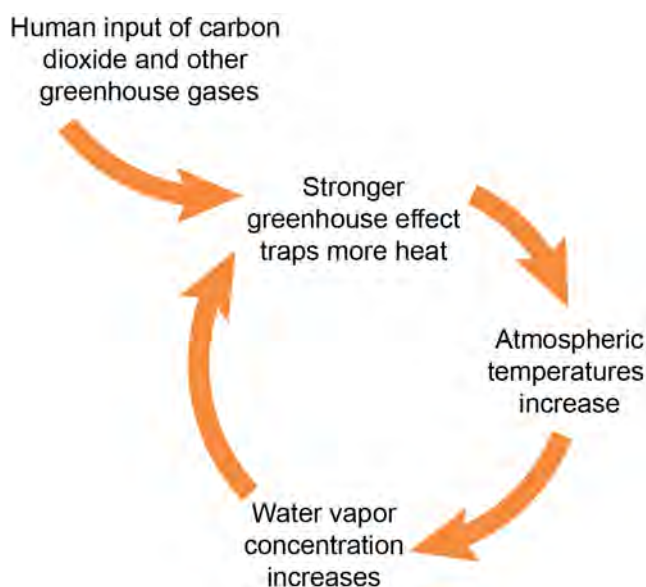


Figure A5.6: As emissions of carbon dioxide and other greenhouse gases increase, the strength of the greenhouse effect increases, which drives an increase in global temperature. This in turn increases the amount of water vapor in the lower atmosphere. Because water vapor is itself a greenhouse gas, the increase in atmospheric water vapor can further strengthen the greenhouse effect. Source: USGCRP.

How are El Niño and climate variability related to climate change?

El Niño and other forms of natural climate variability are not caused by humans, but their frequency, duration, extent, or intensity might be affected by greenhouse gas emissions from human activities. Natural climate variability produces short-term regional changes in temperature and weather patterns, whereas human-caused climate change is a persistent, long-term phenomenon.

Climate variability refers to the natural changes in climate that fall within the observed range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño–Southern Oscillation (ENSO) and other phenomena. ENSO is a quasi-periodic warming or cooling of the of the sea surface temperatures in the tropical eastern Pacific and is often referred to by its phase of El Niño (warm phase) or La Niña (cool phase). These different ENSO phases can have varying ecosystem and economic effects, especially in certain fishing communities, while also influencing weather worldwide (Figure A5.7). In the United States, El Niño conditions generally correspond with warmer than average sea surface and air temperatures along the West Coast, wetter conditions in the Southwest, cooler temperatures in the Southeast, and warmer conditions in the Northeast. In contrast, the La Niña phase of ENSO corresponds to cooler temperature in the U.S. Northwest and dryer and warmer conditions in the Southeast, along with increased upwelling along the West Coast.

Evidence from paleoclimate records suggests that there have been changes in the frequency and intensity of ENSO events in the past. Human-caused climate change might also affect the frequency and magnitude of ENSO events and can exacerbate or ameliorate regional ENSO impacts. For example, if there is a strong La Niña event that results in dry conditions in the Southwest, those conditions may be exacerbated by additional drying due to climate change. ENSO is a complex phenomenon, but new research is shedding light on the many factors influencing how climate change affects the ENSO cycle.¹³

El Niño/La Niña Cause Short-Term Changes in Weather Patterns

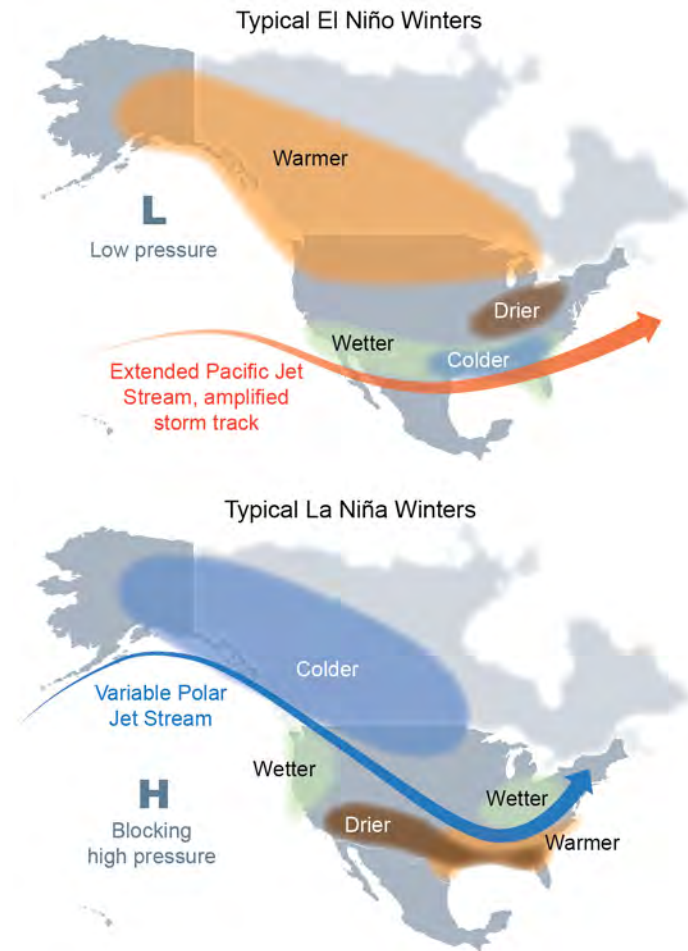


Figure A5.7: El Niño and La Niña events create different weather patterns during winters (January through March) over North America. (top) During an El Niño, there is a tendency for a strong jet stream and storm track across the southern part of the United States. The southern tier of Alaska and the U.S. Pacific Northwest tend to be warmer than average, whereas the southern United States tends to be cooler and wetter than average. (bottom) During a La Niña, there is a tendency for very wave-like jet stream flow over the United States and Canada, with colder and stormier than average conditions across the North and warmer and less stormy conditions across the South. Source: Perlwitz et al. 2017.¹³

Temperature and Climate Projections

What methods are used to record global surface temperatures and measure changes in climate?

Global surface temperatures are measured by using data from weather stations over land and by ships and buoys over the ocean. Global surface temperature records date back more than 300 years in some locations, and near-global coverage has existed since the late 1800s. Multiple research groups have examined U.S. and global temperature records in great detail, taking into account changes in instruments, the time of observations, station location, and any other potential sources of error. Although there are slight differences among datasets—due to choices in data selection, analysis, and averaging techniques—these differences do not change the clear result that global surface temperature is rising.

Climate change is best measured by assessing trends over long periods of time (generally greater than 30 years), which means we need global surface temperature records that include data from before the satellite age. Scientists who obtain, digitize, and collate long-term temperature records take great care to ensure that any potentially skewed measurements—such as a change in instrument method or location or a change in the time of day a recording is made—do not affect the integrity of the dataset. Researchers rigorously examine the data to identify and adjust for any such effects before using it to evaluate long-term climate trends. Different choices in data selection, analysis, and averaging techniques by multiple independent research teams mean that each dataset varies slightly. Even with these variations, however, multiple independently produced results are in very good agreement at both global and regional scales: all global surface temperature datasets indicate that the vast majority of Earth's surface has warmed since 1901 (Figure A5.8).

Scientists also consider other influences that could impact temperature records, such as whether data from thermometers located in cities are skewed by the urban heat island effect, where heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside. When determining climate trends, data corrections to these temperature records have adequately accounted for this effect. At the global scale, evidence of global warming over the past 50 years is still observed even if all of the urban stations are removed from the global temperature record. Studies have also shown that the warming trends of rural and urban areas that are in close proximity essentially match, even though the urban areas may have higher temperatures overall.¹⁴

Global Temperature Increase Shown in Multiple Datasets

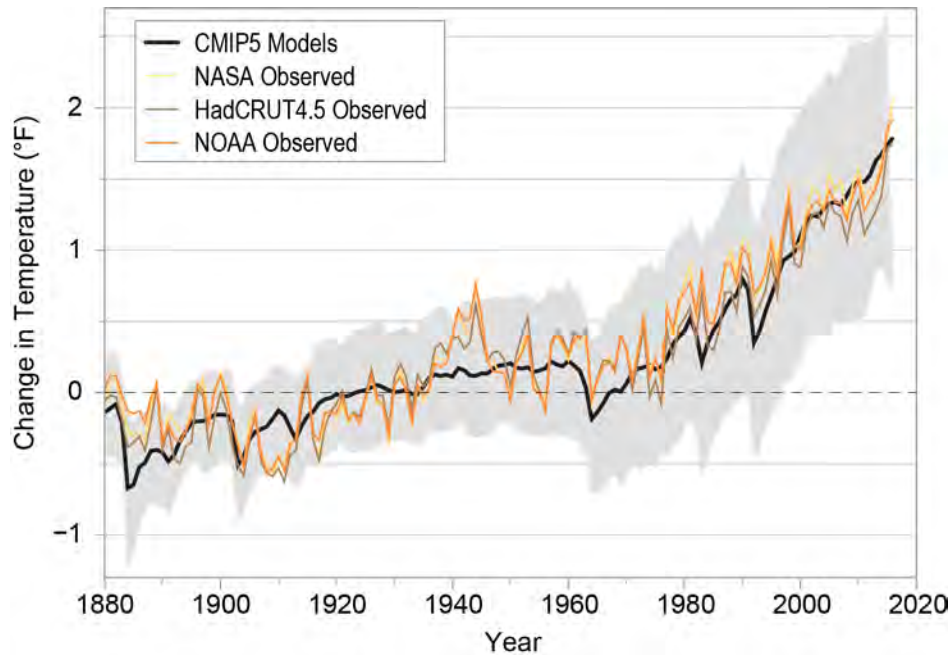


Figure A5.8: This chart shows observations of global annual average temperatures from three different datasets—one from NASA (yellow line), one from NOAA (orange line), and one from the University of East Anglia in conjunction with the United Kingdom’s Met Office (HadCRUT4.5, brown line)—along with historical simulations of global temperature from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble of climate models (black line). The lines show annual differences in temperature relative to the 1901–1960 average. Small differences among datasets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. Source: adapted from Knutson et al. 2016.¹⁵

Were there predictions of global cooling in the 1970s?

No. A review of the scientific literature from the 1970s shows that the broad climate science community did not predict “global cooling” or an “imminent” ice age. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Scientific understanding of what are called the Milankovitch cycles (cyclical changes in Earth’s orbit that can explain the onset and ending of ice ages) led a few scientists in the 1970s to contemplate that the current warm interglacial period might be ending soon, leading to a new ice age over the next few centuries. These few speculations were picked up and amplified by the media. But at that time there were far more scientific articles describing how warming would occur from the increase in atmospheric concentrations of greenhouse gases from human activities, including the burning of fossil fuels (Figure A5.9). The latest information suggests that if Earth’s climate was being controlled primarily by natural factors, the next cooling cycle would begin sometime in the next 1,500 years. However, humans have so altered the composition of the atmosphere that the next ice age has likely now been delayed. That delay could potentially be tens of thousands of years.⁶

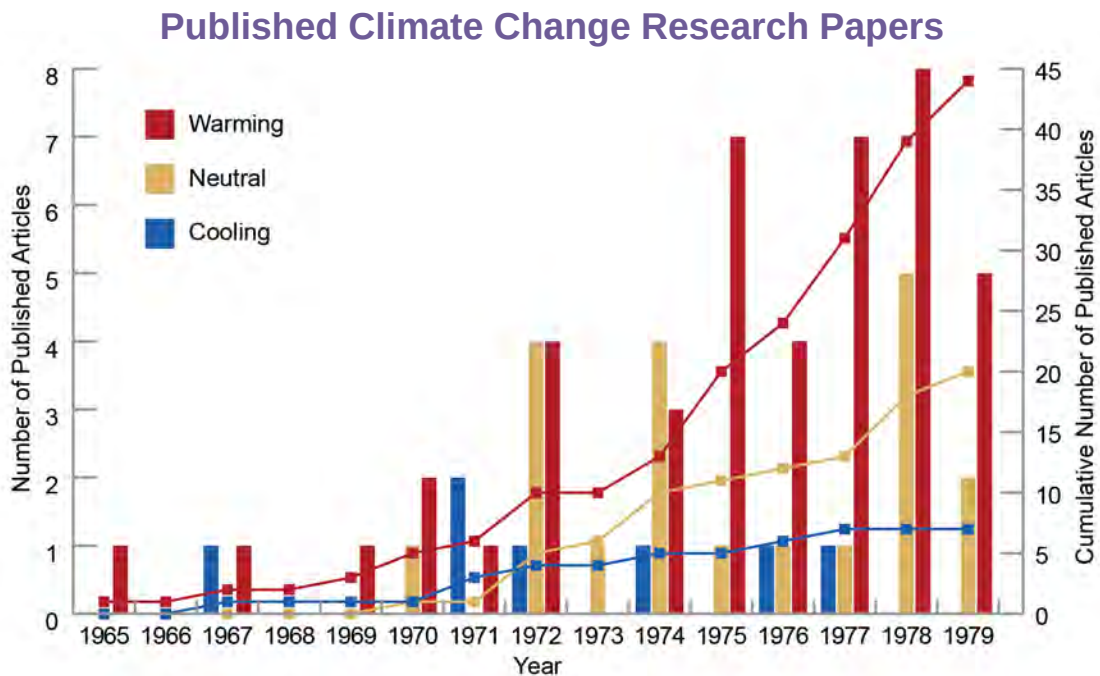


Figure A5.9: This chart compares the number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories published from 1965 to 1979. The bars indicate the number of articles published per year. The lines with squares indicate the cumulative number of articles published. Over this period the literature survey found 7 papers suggesting future cooling (blue line), 20 neutral (yellow line), and 44 warming (red line). Source: Peterson et al. 2008.¹⁶

How are temperature and precipitation patterns projected to change in the future?

Our world will continue to warm in the future because of historic emissions of greenhouse gases (GHGs), but the amount of warming will depend largely on the level of future emissions of GHGs and the choices humans make. If humans continue burning fossil fuels at or above our current rate through the end of the century, scientists project Earth will warm about 9°F, relative to preindustrial times (prior to 1750). Precipitation is projected to still be seasonally and regionally variable, but on average, projections show high-latitude areas getting wetter and subtropical areas getting drier. The frequency and intensity of very heavy precipitation are expected to increase, increasing the likelihood of flooding. Climate change will not affect all places in the same way or to the same degree but will vary at regional levels.

In the coming decades, scientists project that global average temperature will continue to increase (Ch. 2: Climate), although natural variability will continue to play a significant role in year-to-year changes. Sizeable variations from global average changes are possible at the regional level. Even if humans drastically reduce levels of GHG emissions, near-term warming will still occur because there is a lag in the temperature response to changes in atmospheric composition (Figure A5.10).

Over the next couple decades, natural variability and the response of Earth's climate system to historic emissions will be the primary determinants of observed warming. After about 2050, however, the rate and amount of emissions of GHGs released by human activities, as well as the response of Earth's climate system to those emissions, will be the primary determining factors in changes in global and regional temperature (Figure A5.13) (see also Ch. 2: Climate). Efforts to rapidly and significantly reduce emissions of GHGs can still limit the global temperature increase to 3.6°F (2°C) by the end of the century relative to preindustrial levels.¹⁷

Precipitation patterns are also expected to continue to change throughout this century and beyond. The trends observed in recent decades are expected to continue, with more precipitation projected to fall in the form of heavier precipitation events.³ Such events increase the likelihood of flooding, even in drought-prone areas. As with increases in global average temperature, large-scale shifts towards wetter or drier conditions and the projected increases in heavy precipitation are expected to be greater under higher GHG emissions scenarios (for example, RCP8.5) versus lower ones (for example, RCP4.5). Projected warming is also expected to lead to an increase in the fraction of total precipitation falling as rain rather than snow, which reduces snowpack on the margins of areas that now have reliable snowpack accumulation during the cold season (see, for example, Ch. 24: Northwest, KM 2).

Observed and Projected Changes in Global Temperature

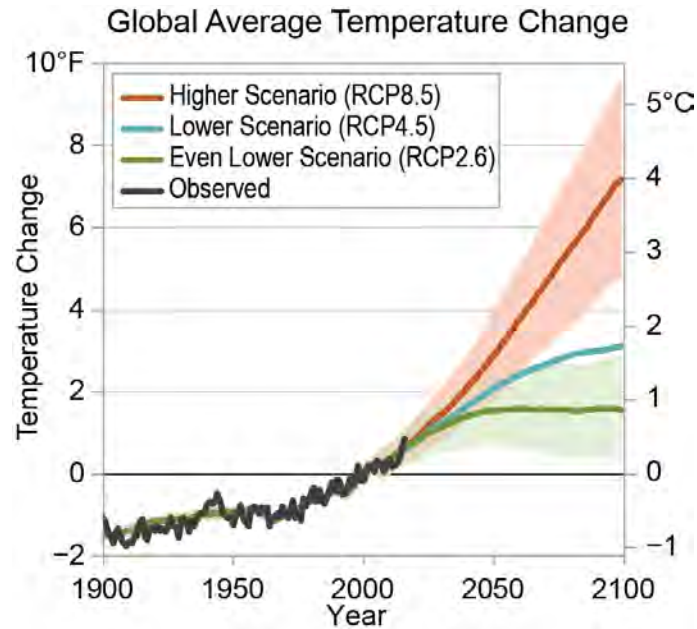


Figure A5.10: This figure shows both observed and projected changes in global average temperature. Under a representative concentration pathway (RCP) consistent with a higher scenario (RCP8.5; red) by 2080–2099, global average temperature is projected to increase by 4.2°–8.5°F (2.4°–4.7°C; burnt orange shaded area) relative to the 1986–2015 average. Under a lower scenario (RCP4.5; blue) global average temperature is projected to increase by 1.7°–4.4°F (0.9°–2.4°C; range not shown on graph) relative to 1986–2015. Under an even lower scenario (RCP2.6; green) temperature increases could be limited to 0.4°–2.7°F (0.2°–1.5°C; green shaded area) relative to 1986–2015. Limiting the rise in global average temperature to less than 2.2°F (1.2°C) relative to 1986–2015 is approximately equivalent to 3.6°F (2°C) or less relative to preindustrial temperatures. Thick lines within shaded areas represent the average of multiple climate models. The shaded regions illustrate the 5% to 95% confidence intervals for the respective projections. Source: adapted from Wuebbles et al. 2017.⁴

How do computers model Earth's climate?

Global climate models enable scientists to create “virtual Earths,” where they can analyze causes and effects of past changes in temperature, precipitation, and other climate variables. Today’s climate models can accurately reproduce broad features of past and present climate, such as the location and strength of the jet stream, the spatial distribution and seasonal cycle of precipitation, and the natural occurrence of extreme weather events, such as heat and cold waves, droughts and floods, and hurricanes. They also can reproduce historic natural cycles, such as the periodic occurrence of ice ages and interglacial warm periods, as well as the human-caused warming that has occurred over the last 50 years. While uncertainties remain, scientists have confidence in model projections of how climate is likely to change in the future in response to key variables, such as an increase in human-caused emissions of greenhouse gases, in part because of how accurately they can represent past climate changes.

Climate models are based on equations that represent fundamental laws of nature and the many processes that affect Earth’s climate system. By dividing the atmosphere, land, and ocean into smaller spatial units to solve the equations, climate models capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over longer time frames, these models simulate wind patterns, high- and low-pressure systems, ocean currents, ice and snowpack accumulation and melting, soil moisture, extreme weather occurrences, and other environmental characteristics that make up the climate system (Figure A5.11).¹⁸

Some important processes, including cloud formation and atmospheric mixing, are represented by approximate relationships, either because the processes are not fully understood or they are at a scale that a model cannot directly represent. These approximations lead to uncertainties in model simulations of climate. Approximations are not the only uncertainties associated with climate models, as discussed in the FAQ “What are key uncertainties when projecting climate change?”

Comparison of Climate Models and Observed Temperature Change

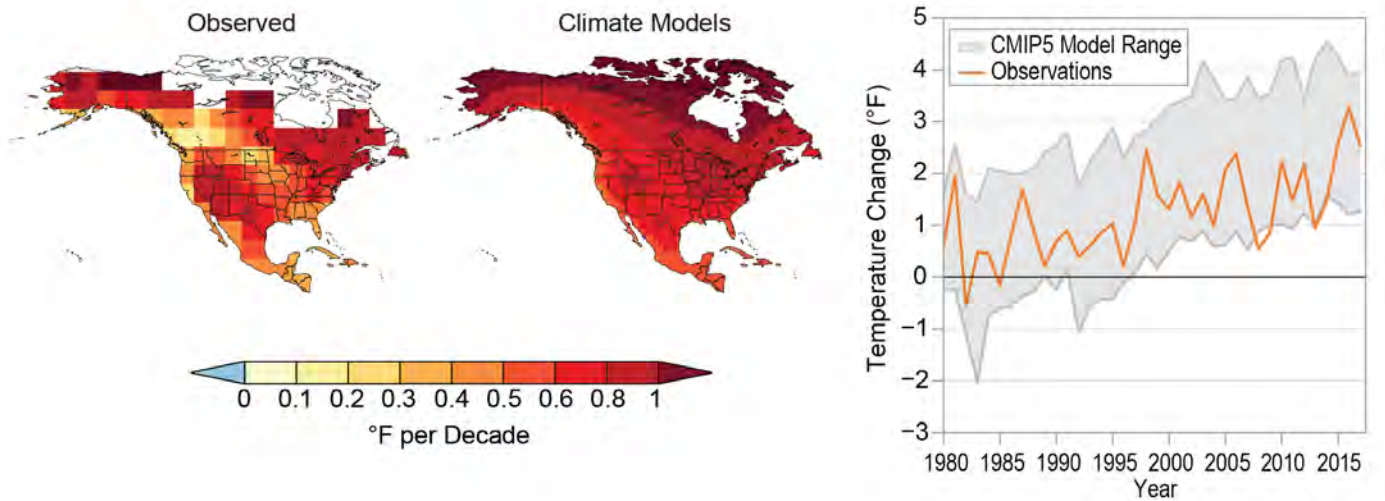


Figure A5.11: Climate simulations (right map) can capture the approximate geographical patterns and magnitude of the surface air temperature trend seen in observational data for the period 1980–2017 (left map). The warming pattern seen in the right map is an average based on 43 different global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The graphical representation shows the range of temperature changes simulated by the models for North America (relative to 1901–1960; gray shading, 5th to 95th percentile range) overlaid by the observed annual average temperatures over North America (orange line). The observed temperature changes are a result of both human contributions to recent warming and natural temperature variations. Averaging the simulations from multiple models suppresses the natural variations and thus shows mainly the human contribution, which is part of the reason small-scale details are different between the two maps. Sources: (maps) adapted from Walsh et al. 2014⁶ (and graph) NOAA NCEI and CICS-NC.

Can scientists project the effects of climate change for local regions?

Yes, though there are limitations. With advances in computing power, the future effects of climate change can be projected more accurately for local communities. Local high-resolution (down-scaled) climate modeling can be used to produce data at a scale of 1–20 miles. These downscaled projections show climate-related impacts at the local level and can be an important tool for community planners and decision-makers.

One significant research focus recently has been to develop models of climate impacts on a relatively small geographic scale. Most global climate projections use grid units that may be too coarse to properly represent mountains, coastlines, and other important features of a local landscape. Recently, two different approaches have been used by scientists to project local climate conditions.

The first is a statistical approach that uses local observations in conjunction with global models to project future changes. The local observations required for this approach are available only for limited regions and for a few climate variables (mainly temperature and precipitation; Figure A5.12).

The second method is a so-called dynamical approach that uses an additional high-resolution computer model—similar to a weather prediction model—to account for complex topography and varying land cover that can impact climate on the local level. High-resolution dynamical models are complete enough to simulate numerous climate variables (temperature, precipitation, winds, humidity, surface sunlight, etc.) and do not require the local observations required for the statistical approach. However, these models require an immense amount of computing power. Today's most powerful supercomputers enable climate scientists to examine the effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase 100-fold or more, improving climate projections and models on both the global and local levels.

It should also be noted that both statistical and dynamical approaches have biases and errors that, when combined with uncertainties from global model simulations, can reduce the level of confidence in these more localized projections (see Hayhoe et al. 2017¹⁸ for more details).

Climate Modeling for Smaller Regions

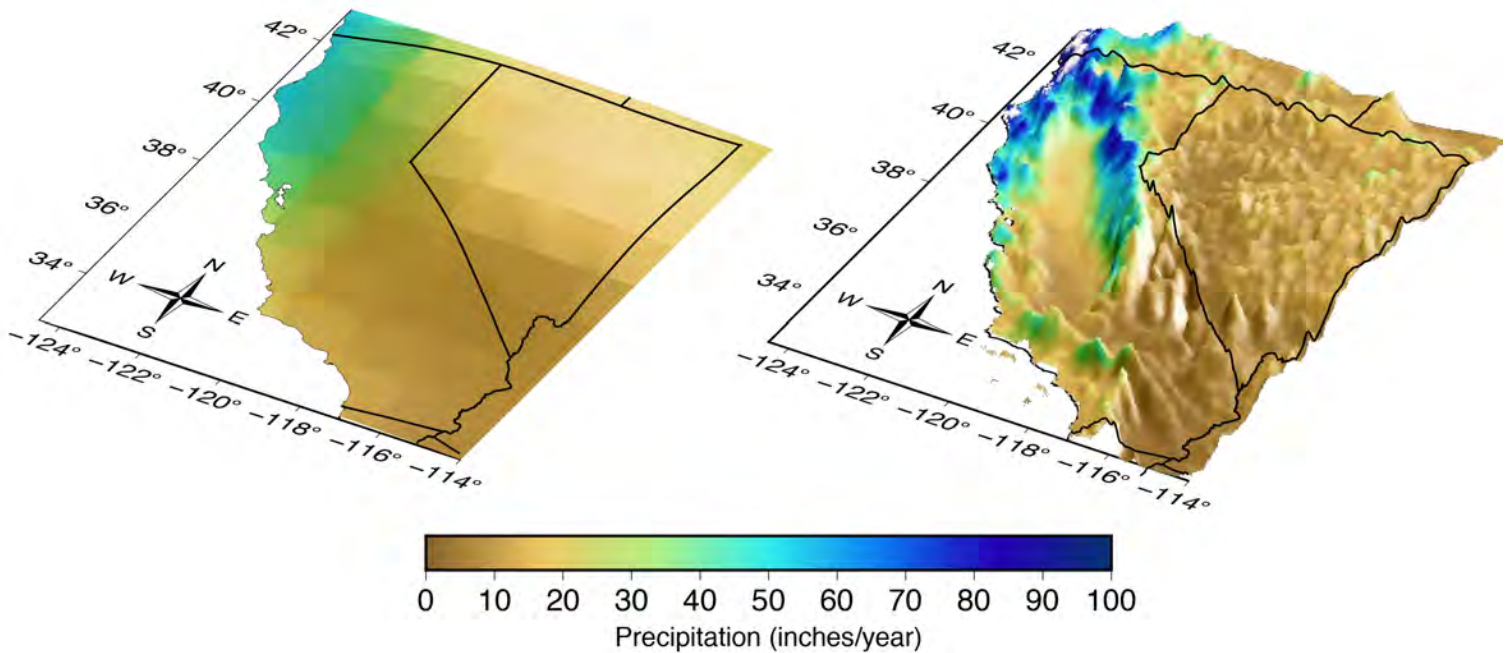


Figure A5.12: The figure shows projections of annual precipitation (in inches) in California and Nevada in a global climate model with a resolution of 100 miles (left) and, after using a statistical model to account for the effects of topography, at a resolution of 3.6-miles (right). The global model has only a few grid cells over the entire state of California, so it does not resolve the coastal mountain range, interior valley, or Sierra Nevada on the border with Nevada. The precipitation field in the right panel, by contrast, captures the wet conditions on the west slopes of the mountains and the dry, rain shadow region to the east of the mountains. The topography has been exaggerated for clarity and by the same amount in both panels. Source: UCSD Scripps Institute of Oceanography.

What are key uncertainties when projecting climate change?

The precise amount of future climate change that will occur over the rest of this century is uncertain, mainly due to uncertainties in emissions, natural variability, and differences in scientific models.

First, projections of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change due to changes in population, energy use, technology, and economics. Society may choose to reduce emissions or continue on a pathway of increasing emissions. The differences in projected future climate under different scenarios are generally small for the next few decades. By the second half of the century, however, human choices, as reflected in these scenarios, become the key determinant of future climate change (Figure A5.13).

A second source of uncertainty is natural variability, which affects the climate over timescales from months to decades. These natural variations are largely unpredictable, such as a volcanic eruption, and are superimposed on the warming from increasing greenhouse gases (GHGs).

A third source of uncertainty involves limitations in our current scientific knowledge. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and aerosol effects). Additionally, climate sensitivity, or how much the climate will warm with a given increase in GHGs (often a doubling of GHG from preindustrial levels), is still a major source of uncertainty. As a result, different models produce small differences in projections of global average change. Scientists often use multiple models to account for the variability and represent this as a range of projected outcomes.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in projections of climate in the future. For example, as the Arctic warms, carbon trapped in permafrost may be released into the atmosphere, increasing the initial warming due to human-caused emissions of GHGs, or an ice sheet may collapse, leading to faster than expected sea level rise.

However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, with those bounds determined not only from the differences in how climate responds to a doubling of GHG concentrations among models but also by utilizing information about climate changes in the past (see Hayhoe et al. 2017¹⁸ for more details).

Key Uncertainties in Temperature Projections

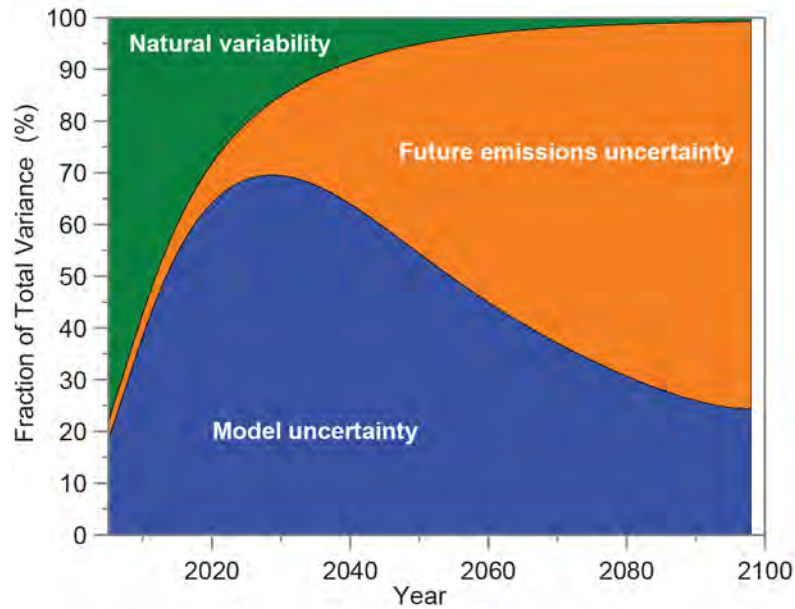


Figure A5.13: The graph shows the change in the fraction of total variance (uncertainty) of three components of total uncertainty in decadal average surface air temperature projections for the contiguous United States. Green represents natural variability, orange represents future emissions uncertainty, and blue represents model or scientific uncertainty (including in climate sensitivity). As the time period becomes more distant, the impact of natural variability becomes less significant due to the smaller variability over a larger period. Future emissions uncertainty increases as time progresses, since we are unable to determine the exact choices that will be made by humans in the future. The influence of model uncertainty on the total uncertainty of how climate will change decreases as the century progresses, due to advances in science and the creation of more accurate and precise assessment systems. This figure shows total uncertainty for the lower 48 states—as the size of the region is reduced, the relative importance of natural variability increases. It is important to note that this figure shows the fractional sources of uncertainty. The total amount of uncertainty increases through time. Source: adapted from Hawkins and Sutton 2009.¹⁹ ©American Meteorological Society. Used with permission.

Is it getting warmer everywhere at the same rate?

Our world is warming overall, but temperatures are not increasing at the same rate everywhere. The average global temperature is projected to continue increasing throughout the remainder of this century due to greenhouse gas (GHG) emissions from human activities. Generally, high latitudes are expected to continue warming more than lower latitudes; coastal and island regions are expected to warm less than interior continent regions.

Temperature changes at a given location are a function of multiple factors, including global and local forces, and both human and natural influences. Though Earth's average temperature is rising, some locations could be cooling due to local factors. In some places, including the U.S. Southeast, temperatures do not show a warming trend over the last century as a whole, although they have been increasing since the 1960s (Ch. 19: Southeast). Possible causes of the observed lack of warming in the Southeast during the 20th century include increased cloud cover and precipitation, increases in the presence of fine particles (called aerosols) in the atmosphere, expanding forests, decreases in the amount of heat conducted from land due to increases in irrigation, and multidecadal variability in sea surface temperatures in both the North Atlantic and the tropical Pacific Oceans. At smaller geographic scales and time intervals, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale. A lack of warming or a decrease in temperature at an individual location does not negate the fact that, overall, the planet is warming.

Alaska, in contrast to the U.S. Southeast, has been warming twice as fast as the global average since the middle of the 20th century (Ch. 26: Alaska). Statewide average temperatures for 2014–2016 were notably warmer as compared to the last few decades, with 2016 being the warmest on record. Daily record high temperatures in the contiguous United States are now occurring twice as often as record low temperatures. In Alaska, starting in the 1990s, record high temperatures occurred three times as often as record lows, and in 2015, an astounding nine times as often (Ch. 26: Alaska).

Because Earth's climate system still has more energy entering than leaving, global warming has not yet equilibrated to the load of increased GHGs that have already accumulated in the atmosphere (for example, the oceans are still warming over many layers from surface to depth). Some GHGs have long lifetimes (for example, carbon dioxide can reside in the atmosphere for a century or more). Thus, even if the emissions of GHGs were to be sharply curtailed to bring them back to natural levels, it is estimated that Earth is committed to continued warming of more than 1°F by 2100.

At the global scale, some future years will be cooler than the preceding year; some decades could even be cooler than the preceding decade (Figure A5.14). Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future as a result of natural variability and other factors. Nonetheless, each successive decade in the last 30 years has been the warmest in the period of reliable instrumental records (going back to 1850; Figure A5.15). In fact, the rate of warming has accelerated in the past several decades, and 17 of the 18 warmest years have occurred since 2001 (see FAQ “What do scientists mean by the

‘warmest year on record?’). Based on this historical record and assessed scenarios for the future, it is expected that future global temperatures, averaged over climate timescales of 30 years or more, will be higher than preceding periods as a result of emissions of CO₂ and other GHGs from human activities (Ch 2: Climate).

Temperature Change Varies by Region

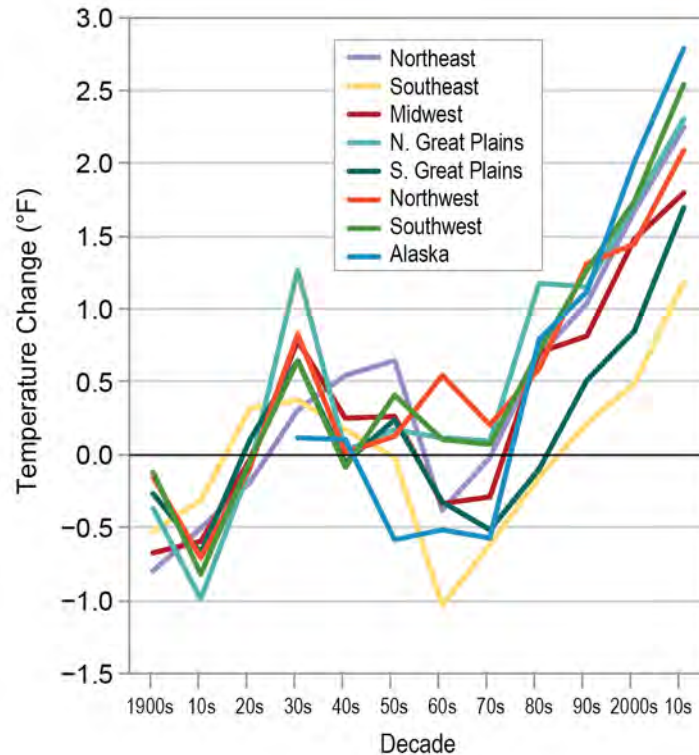


Figure A5.14: This graph shows changes in decadal-averaged temperature relative to the 1901–1960 average for eight of the ten NCA regions (see Front Matter, Figure 1). This figure shows how regional temperatures can be quite variable from decade to decade. All regions, however, have experienced warming over the last three decades or more. The most recent decade, the 2010s, refers to the 6-year period of 2001–2016. Source: adapted from Walsh et al. 2014.⁶ Comparable data is not currently available for the Hawai'i and U.S.-Affiliated Pacific Islands or U.S. Caribbean regions.

Average Global Temperature Is Increasing

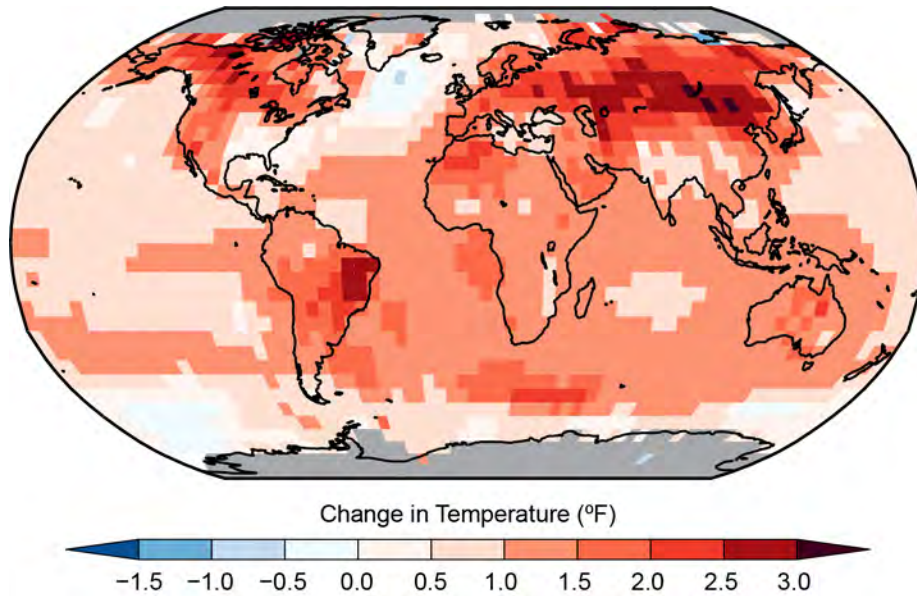


Figure A5.15: This map shows the observed changes in temperature for the 1986 to 2015 period relative to the 1901–1960 average. Shades of red indicate warming, while shades of blue indicate cooling. There are insufficient data in the Arctic Ocean and Antarctica for computing long-term changes. There are substantial regional variations in trends across the planet, though the overall trend is warming. Source: Vose et al. 2012.²⁰

What do scientists mean by the “warmest year on record”?

When scientists declare it the “warmest year on record,” they mean it’s the warmest year since modern global surface temperature record keeping began in 1880. Global temperature data from NASA show that 2016 marked the sixth time this century that a new record high annual average temperature was set (along with 2002, 2005, 2010, 2014, and 2015) and that 17 of the 18 warmest years have occurred since 2001.

The “warmest year on record” means it is the warmest year in more than 130 years of modern record keeping of global surface temperature. Prior to 1880, observations did not cover a large enough area of Earth’s surface to enable an accurate calculation of the global average temperature. To calculate the value in recent times, scientists evaluate data from roughly 6,300 stations around the world, on land, ships, and buoys.

The year the last National Climate Assessment was published, 2014, was the warmest year on record at the time, but it was surpassed by 2015, which was then surpassed by 2016. Data from NASA shows that 17 of the 18 warmest years have occurred since 2001, and the 6 warmest years on record have occurred this century (Figure A5.16). However, the global surface temperature is affected by natural variability in addition to climate change, so it is not expected that each year will set a new temperature record.

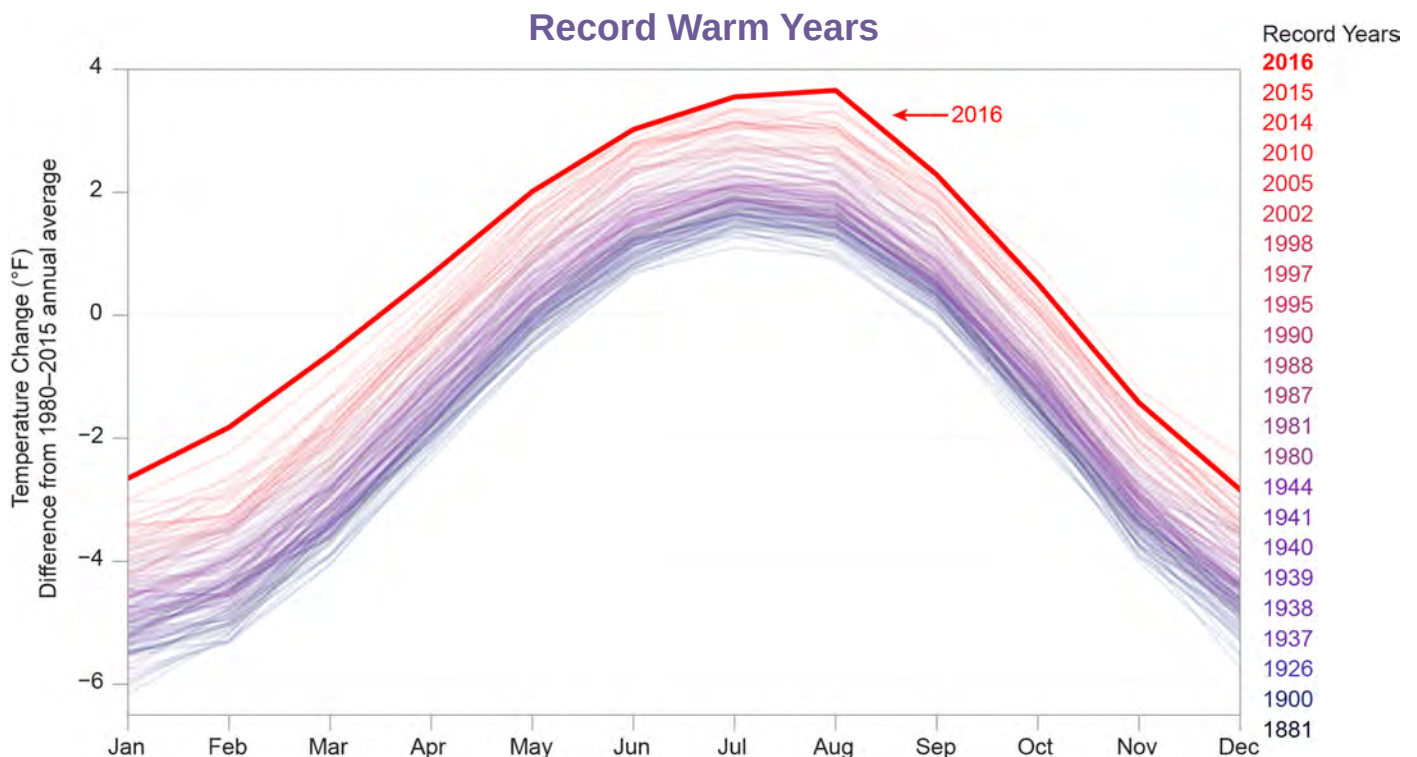


Figure A5.16: This graph shows global, monthly averaged temperature, relative to the 1980–2015 average, plotted over annual temperature cycles from 1880–2017. Record-breaking warm years are listed in the column to the right. The colored lines, shading from gray to blue to purple to red, indicate the years from 1880 to 2017, with 2016, bolded in red, being the hottest year on record. An animation of the complete time series is available online at <https://nca2018.globalchange.gov/chapter/appendix-5/#fig-a5-16>. Source: NASA.

How do climate projections differ from weather predictions?

The range of possible weather conditions at a specific location on any given day can vary considerably. The climate varies far less for that same location, because it is a measure of weather conditions averaged over 30 years or more. Because the range of possible climate conditions at a given location is much smaller than the range of possible weather conditions, scientists are able to project climate conditions decades into the future.

Projecting how climate may change decades in the future is a different scientific issue than forecasting weather a few days from now. Weather prediction means determining the exact location, time, and magnitude of specific events. Because the range of possible weather conditions can vary so widely, the weather forecast is extremely sensitive to even the smallest uncertainties or errors in our description of the state of the atmosphere at the start of a forecast. The impact of those uncertainties magnifies over time, which makes it very difficult to predict specific weather events at a given location more than a week or two into the future.

Because climate is the average weather at a given location over long periods of time (three decades or more), the range of possible climate conditions at a given location is much smaller than the range of possible weather conditions. For example, the daytime high temperature at a given location may vary by 30°F or more over the course of a day, while the annual average temperature over 30 years may vary by no more than a few degrees (Figure A5.17).

We can project how climate may change over time in response to natural forces, such as changes in incoming solar radiation, and in response to human activities, such as increasing the abundance of greenhouse gases (GHGs) or decreasing particle pollution. These projections are usually expressed in terms of probabilities describing a range of possible outcomes, not in the sort of exact (deterministic) language of many weather forecasts.

The difference between predicting weather and projecting climate is sometimes illustrated with a public health analogy. While it is impossible for us to determine the exact date and time when a particular individual will die, we can easily calculate the average age of death of all Americans for a time period in the past. In this case, weather is like the individual, while climate is like the average. To extend this analogy into the realm of climate change, we can also calculate the average life expectancy of Americans who smoke. We can predict that, on average, smokers will not live as long as nonsmokers. Similarly, we can project what the climate will be like if we emit lower levels of GHGs and what it will be like if we emit more.

U.S. Annual Average Temperature

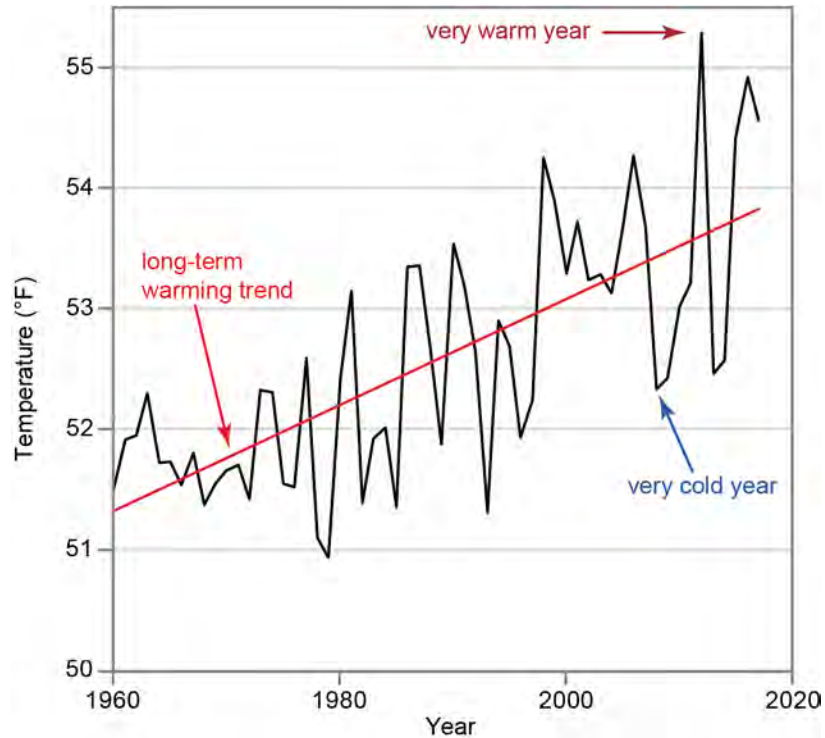


Figure A5.17: This figure shows the annual average surface temperature for the contiguous U.S. (black line) from 1960 to 2017, and the long-term warming trend (red line). Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. Year-to-year and even decade-to-decade, conditions do not necessarily tell us much about long-term changes in climate. One cold year, or even a few cold years in a row, does not contradict a long-term warming trend, just as one hot year does not prove it. Source: adapted from Walsh et al. 2014.⁶

Climate, Weather, and Extreme Events

Was there a “hiatus” in global warming?

Temperature records show that the long-term (30 years or longer) trend in increasing surface temperatures has not ceased. The rate of warming has been faster during some decades and slower during others, but these relatively short periods of time are not the basis for scientists’ conclusion that sustained global warming is occurring.

“Global warming” refers to the increase in global average surface temperature that has been observed for more than a century. This warming is clearly revealed in both the surface temperature record and in satellite measurements of lower-atmospheric (troposphere) temperature. While the long-term trend shows warming, scientists expect that the rate of warming will vary from year to year or decade to decade due to the variability inherent in the climate system, or due to short-term changes in climate forcings, such as aerosols (dust, pollution, or volcanic particles) or incoming solar energy (Figure A5.18).

Temporary slowdowns in the rate of warming have occurred earlier in the historical record, even as carbon dioxide concentrations continued to rise. Temporary speedups have also occurred, most notably from the early 1900s to the 1940s and from the 1970s to the late 1990s. Computer simulations of both historical and future climate produce similar variations in the rate of warming, making recent variations in short-term temperature trends unsurprising.

From the mid-1940s to the mid-1970s, there was almost no increase in global temperature, possibly related to an increase in volcanic activity and/or human-caused aerosol emissions. Most notably, for the 15 years following the 1997–1998 El Niño event, the observed rate of temperature increase was smaller than what was projected by some climate models. However, during this period other indicators of climate change continued previous trends associated with warming, such as increasing ocean heat content and decreasing arctic sea ice extent (Figure A5.19; see Wuebbles et al. 2017,⁴ Box 1.1).