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UNITED STATES DISTRICT COURT

DISTRICT OF OREGON

KELSEY CASCADIA ROSE JULIANA; **XIUHTEZCATL TONATIUH M.**, through his Guardian Tamara Roske-Martinez; et al.,

Plaintiffs,

v.

The UNITED STATES OF AMERICA; et al.,

Defendants.

Case No.: 6:15-cv-01517-AA

DECLARATION OF JULIA A. OLSON in Support of Plaintiffs' Response in Opposition to Motion for Limited Intervention

I, Julia A. Olson, hereby declare and if called upon would testify as follows:

1. I am an attorney of record in the above-entitled action. I make this Declaration in support of Plaintiffs' Response in Opposition to Motion for Limited Intervention. I have personal knowledge of the facts stated herein, except as to those stated upon information and belief, and if called to testify, I would and could testify competently thereto.
2. On June 7, 2021, my co-counsel Philip Gregory, Andrea Rodgers, and I had a telephone call with Edmund LaCour, Solicitor General of Alabama, and his colleague Thomas Wilson, to meet and confer on their proposed motion to intervene. Mr. LaCour informed us that the Proposed Intervenor States intended to intervene in the case for the limited purpose of getting the case dismissed in light of the Ninth Circuit's January 2020 decision. He stated the Proposed Intervenor States wanted to make sure that their arguments are sufficiently advocated for in the District Court, the Ninth Circuit, and the Supreme Court, if needed. This position is also indicated in their Motion for Limited Intervention: "Moreover, the States are prepared to press arguments against amending the complaint before the Ninth Circuit and Supreme Court if those arguments prove unpersuasive to this Court." Doc. 475 at 21. Mr. LaCour also stated that the case was a "newsworthy suit" and that they had heard about the Ninth Circuit decision in January 2020.
3. In their Motion for Limited Intervention, the Proposed Intervenor States reference their "'quasi-sovereign interests in the health and well-being – both physical and economic – of [their] residents' as *parens patriae*." Doc. 475 at 14. Yet the Proposed Intervenor States have not provided any evidence supporting this assertion. As part of their opposition, Plaintiffs hereby reference evidence in the record in this case, and submit the

following additional evidence to establish that the nation's fossil fuel energy system harms the health and wellbeing of the residents of the 18 Proposed Intervenor States. This new evidence is documented in the U.S. Government's Fourth National Climate Assessment, a publicly available, government document of which this Court may take judicial notice.

4. There is ample evidence in the record of this case documenting the economic harms, disproportionately imposed on children, caused by the nation's fossil fuel energy system. *See, e.g.,* Doc. 257-1 (Expert Report of Frank Ackerman); Doc. 264-1 (Expert Report of Steven W. Running); Doc. 266-1 (Expert Report of Joseph E. Stiglitz); Doc. 272-1 (Expert Report of Susan E. Pacheco and Jerome A. Paulson).

5. The funds the Proposed Intervenor States receive from the federal government for oil and gas leasing are a drop in the bucket compared to the costs the Proposed Intervenor States have and will have to incur due to the impacts of climate change. It is well documented in the U.S. Government's Fourth National Climate Assessment, which was issued after this Court certified the case for interlocutory appeal, that climate change-related events have already cost the Proposed Intervenor States multiple billions of dollars and this price tag is expected to increase as the climate crisis worsens. *See* U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 19: Southeast* 758 (2018), attached hereto as **Exhibit 1**.

6. For example, in the Southeast, which includes many of the Proposed Intervenor States, "[t]he combined impacts of sea level rise and storm surge in the Southeast have the potential to cost up to $60 billion each year in 2050 and up to $99 billion in 2090 under a

higher scenario (RCP8.5). Even under a lower scenario (RCP4.5), projected damages are $56 and $79 billion in 2050 and 2090, respectively (in 2015 dollars, undiscounted)."[1]

7. Sea level rise, a consequence of climate change, is causing recurrent tidal flooding in Charleston, South Carolina. "Charleston experienced all-time record high tide flood occurrences in 2015 (38 days) and 2016 (50 days). By 2045, Charleston is projected to experience up to 180 high tide flood events a year. The City of Charleston estimated that each flood event that affects the crosstown costs $12.4 million (in 2009 dollars). Over the past 50 years, the resultant gross damage and lost wages have totaled more than $1.53 billion (dollar year not specified)."[2]

8. Extreme precipitation events, another consequence of climate change, cause significant flooding damages in the Southeast. For example, "[an extreme precipitation] event in northern Louisiana on March 8–12, 2016, caused $2.4 billion in damages (in 2017 dollars; $2.3 billion in 2015 dollars) and five casualties, illustrating that inland low-lying areas in the Southeast region are also vulnerable to flooding impacts."[3]

9. Hurricane Harvey caused $133.8 billion dollars of damage in Texas in 2017.[4]

10. Extreme rainfall events caused by climate change resulted in four separate billion-dollar flood events in the Southeast between 2014–2016, including Hurricane Matthew, which

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[1] Exhibit 1, U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 19: Southeast* 758 (2018).
[2] *Id.* at 760.
[3] *Id.* at 763.
[4] NOAA, *Billion-Dollar Weather and Climate Disasters: Events*, https://www.ncdc.noaa.gov/billions/events/US/1980-2021 (last visited July 6, 2021), attached hereto as **Exhibit 2**.

caused over $10 billion in damages in October 2016, and Louisiana flooding, which also caused over $10 billion in damages in August 2016.[5]

11. Total disasters in 2017 cost $306.2 billion in damages, many of which occurred in the Proposed Intervenor States.[6]

12. To adapt to impacts from sea-level rise from climate change, Louisiana has developed a 50-year, $50-billion strategic plan.[7]

13. "By 2090, under a higher [emissions] scenario (RCP8.5), the Southeast is projected to have the largest heat-related impacts on labor productivity in the country, resulting in average annual losses of 570 million labor hours, or $47 billion (in 2015 dollars, undiscounted), a cost representing a third of total national projected losses, although these figures do not include adaptations by workers or industries."[8]

14. Proposed Intervenor States such as Montana, North Dakota, and Nebraska have ecosystems that "provide recreational opportunities and other valuable goods and services that are ingrained in the region's cultures and at risk in a changing climate," such as fishing.[9] "[S]hifts 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)."[10]

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[5] Exhibit 1, U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 19: Southeast* 763 (2018).
[6] *Id.* at 766.
[7] *Id.* at 775.
[8] *Id.* at 780.
[9] U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 22: Northern Great Plains* 957 (2018), attached hereto as **Exhibit 3**.
[10] *Id*. at 958.

15. In northwestern Wyoming and western Montana, the season length for cross-country skiing and snowmobiling, $4.6 million and $2.3 million industries, respectively, is expected to decline by up to 100% and similar losses are expected for the downhill skiing industry, which is a $275 million industry.[11]

16. In the Northern Great Plains, "[i]ncreasing 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)."[12]

17. In Alaska, "[t]he 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)."[13]

18. "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," with estimates ranging to be between $3.6 and $6.1 billion (in 2008 dollars), translating "to an average of $250 to $420 million per year (in 2015 dollars)."[14]

19. "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."[15]

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[11] *Id*.
[12] *Id*. at 962.
[13] U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 26: Alaska* 1190 (2018), attached hereto as **Exhibit 4**.
[14] *Id*. at 1206-07.
[15] U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 25: Southwest* 1129 (2018), attached hereto as **Exhibit 5**.

20. "Under the higher scenario (RCP8.5), extreme heat in the Southwest . . . 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)."[16]

21. Proposed Intervenor States like Utah have "climate-related vulnerabilities" which "include reduced long-term livestock grazing capacity, reduced feed supply, increased heat stress, and reduced forage quality."[17] "In response to drought (1999-2004), 75% of Utah ranch operations reported major reductions in water supply, forage, and cattle productivity."[18]

22. The federal government has also documented how climate change is harming the health and wellbeing of residents of the Proposed Intervenor States. For example, Southeastern cities are experiencing climate change impacts, including sea level rise, increasing temperatures, extreme heat events, heavy precipitation, flooding, decreased water availability, and increased vector-borne diseases with "numerous consequences for human health."[19]

23. In the Southeastern region, "[m]ore frequent extreme heat episodes and changing seasonal climates are projected to increase exposure linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors."[20]

24. "Heat-related stresses are presently a major concern in the Southeast. . . . The resulting temperature increases are expected to add to the heat health burden in rural, as well as

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[16] *Id.*
[17] *Id.* at 1128.
[18] *Id.*
[19] Exhibit 1, U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 19: Southeast* 746, 749, 752 (2018).
[20] *Id.* at 745.

urban, areas."[21] Increasing temperatures also decrease the productivity of crops, and increase droughts that threaten water supplies.[22]

25. "Workers in the agriculture, forestry, hunting, and fishing sectors together with construction and support, waste, and remediation services work are the most highly vulnerable to heat-related deaths in the United States, representing almost 68% of heat-related deaths nationally. Six of the ten states with the highest occupational heat-related deaths in these sectors are in the Southeast region, accounting for 28.6% of occupational heat-related deaths between 2000 and 2010."[23]

26. "In the Southeast, poor air quality can result from emissions (mostly from vehicles and power plants), wildfires, and allergens such as pollen. The major urban centers in the Southeast are already impacted by poor air quality during warmer months. The Southeast has more days with stagnant air masses than other regions of the country (40% of summer days) and higher levels of fine (small) particulate matter ($PM_{2.5}$), which cause heart and lung disease."[24] "Continued rising temperatures and atmospheric CO_2 levels are projected to further contribute to aeroallergens in [Southeastern] cities."[25]

27. "Climatic conditions are currently suitable for adult mosquitoes of the species *Aedes aegypti*, which can spread dengue, chikungunya, and Zika viruses, across most of the Southeast from July through September . . . . The Southeast is the region of the country with the most favorable conditions for this mosquito and thus faces the greatest threat from diseases the mosquito carries. Climate change is expected to make conditions more

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[21] *Id.* at 777.
[22] *Id.*
[23] *Id.* at 780.
[24] *Id.* at 755.
[25] *Id.*

suitable for transmission of certain vector-borne diseases . . . . Summer increases in dengue cases are expected across every state in the Southeast."[26]

28. "The healthcare system in the Southeast is already overburdened and may be further stressed by climate change. Between 2010 and 2016, more rural hospitals closed in the Southeast than any other region, with Alabama, Georgia, Mississippi, and Tennessee being among the top five states for hospital closures. This strain, when combined with negative health impacts from climate change stressors (such as additional patient demand due to extreme heat and vector-borne diseases and greater flood risk from extreme precipitation events), increases the potential for disruptions of health services in the future."[27]

29. In the Northern Great Plains, "[t]he probability for more very hot days . . . is expected to increase, with potential impacts on agriculture, energy production, human health, streamflows, snowmelt, and fires."[28]

30. "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. The subsistence activities of local residents are also affected, which in turn affects food security, culture, and health."[29]

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[26] *Id.* at 754-55.
[27] *Id.* at 781.
[28] Exhibit 3, U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 22: Northern Great Plains* 952 (2018).
[29] Exhibit 4, U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 26: Alaska* 1190 (2018).

31. "Under continued climate change, projected increases in hot days and extreme heat events in the Southwest . . . will increase the risk of heat-associated deaths."[30]

32. Plaintiffs hereby request that this Court take judicial notice of this significant evidence that continuing the nation's fossil fuel energy system threatens the Proposed Intervenor States' "'quasi-sovereign interests in the health and well-being – both physical and economic – of [their] residents.'" Doc. 475 at 10.

33. The foregoing evidence is not a complete list of harms these Proposed Intervenor States are already experiencing due to climate change, but it adequately supports a conclusion by this Court that any cost-benefit analysis on economic harm to states from maintaining the nation's fossil fuel energy system compared to phasing it out will conclusively demonstrate that maintaining the *status quo* poses dire and largely irreversible economic harm statewide compared to a limited economic impact on one sector of the economy that will be replaced by other forms of energy production.

I declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct. Executed on July 6, 2021 in Eugene, Oregon.

/s/ Julia A. Olson
Julia A. Olson

[30] Exhibit 5, U.S. Global Change Research Program, *Fourth National Climate Assessment, Chapter 25: Southwest* 1129 (2018).

Exhibit 1

19 Southeast

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On the Web: https://nca2018.globalchange.gov/chapter/southeast

19 Southeast

Red mangrove in Titusville, Florida

Key Message 1

Urban Infrastructure and Health Risks

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

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

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

Key Message 3

Natural Ecosystems Will Be Transformed

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

Key Message 4

Economic and Health Risks for Rural Communities

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

Executive Summary

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

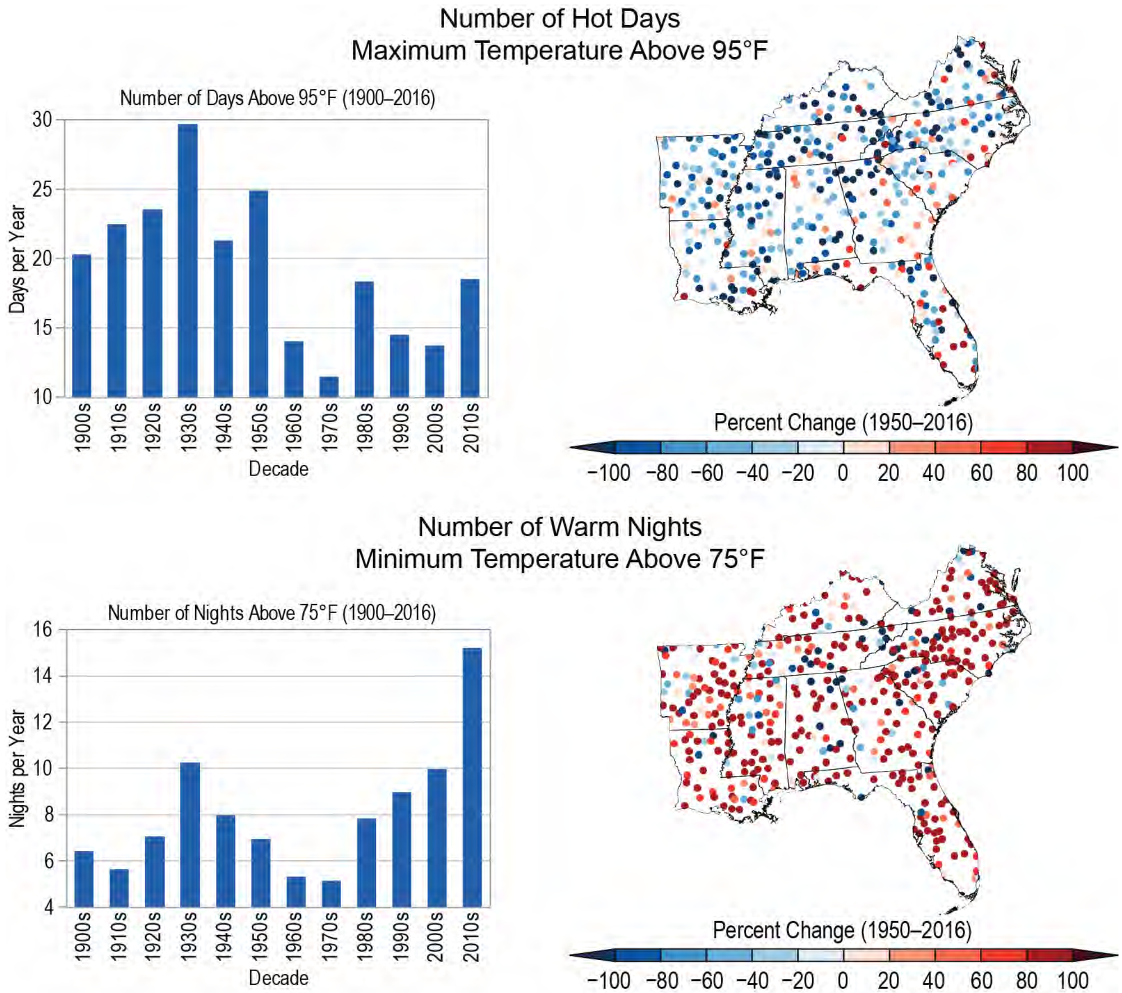
Observed warming since the mid-20th century has been uneven in the Southeast region, with average daily minimum temperatures increasing three times faster than average daily maximum temperatures. The number of extreme rainfall events is increasing. Climate model simulations of future conditions project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

Trends towards a more urbanized and denser Southeast are expected to continue, creating new climate vulnerabilities. Cities across the Southeast are experiencing more and longer summer heat waves. Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors, and the major urban centers in the Southeast are already impacted by poor air quality during warmer months. Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, which will likely have cascading effects across the region. Infrastructure related to drinking water and wastewater treatment also has the potential to be compromised by climate-related events. Increases in extreme rainfall events and high tide coastal floods due to future climate change will impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Sea level rise is contributing to increased coastal flooding in the Southeast, and high tide flooding already poses daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the region.[1,2] There have been numerous instances of intense rainfall events that have had devastating impacts on inland communities in recent years.

The ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change. Sea level rise will result in the rapid conversion of coastal, terrestrial, and freshwater ecosystems to tidal saline habitats. Reductions in the frequency and intensity of cold winter temperature extremes are already allowing tropical and subtropical species to move northward and replace more temperate species. Warmer winter temperatures are also expected to facilitate the northward movement of problematic invasive species, which could transform natural systems north of their current distribution. In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire practices.[3,4,5,6]

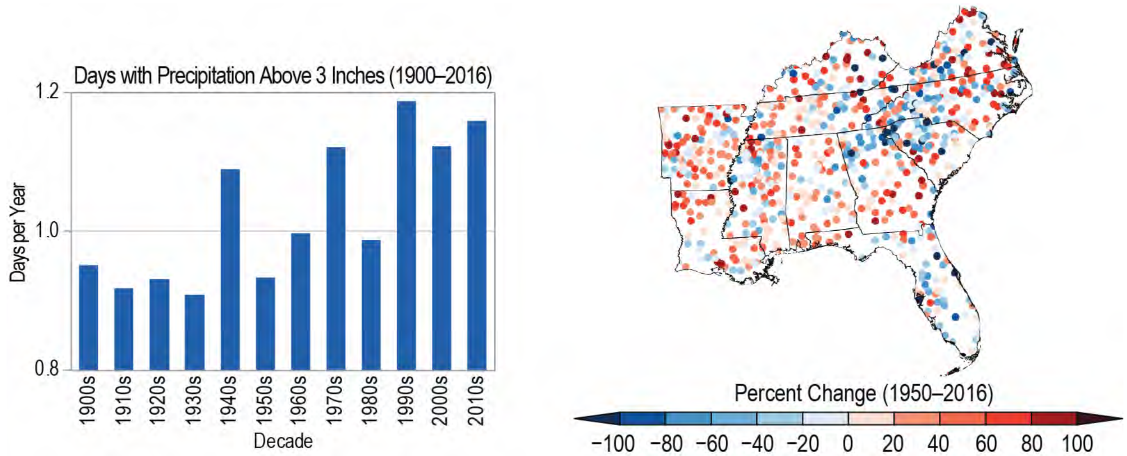
Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate changes. Climate trends and possible climate futures show patterns that are already impacting—and are projected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity. Future temperature increases are projected to pose challenges to human health. Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems.[7] Rural communities tend to be more vulnerable to these changes due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10] In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from future climate changes in the United States. Climate change tends to compound existing vulnerabilities and exacerbate existing inequities. Already poor regions, including those found in the Southeast, are expected to continue incurring greater losses than elsewhere in the United States.

Historical Changes in Hot Days and Warm Nights



Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. *From Figure 19.1 (Sources: NOAA NCEI and CICS-NC).*

Historical Change in Heavy Precipitation



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

Background

Throughout the southeastern United States, the impacts of sea level rise, increasing temperatures, extreme heat events, heavy precipitation, and decreased water availability continue to have numerous consequences for human health, the built environment, and the natural world. This assessment builds on the above concerns described in the Third National Climate Assessment (NCA3) and includes impacts to urban and rural landscapes as well as natural systems. The impacts from these changes are becoming visible as 1) flooding increases stress on infrastructure, ecosystems, and populations; 2) warming temperatures affect human health and bring about temporal and geographic shifts in the natural environment and landscapes; and 3) wildfires and growing wildfire risk create challenges for natural resource managers and impacted communities.

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern (and highest) portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. Embedded in these land- and seascapes is a rich cultural history developed over generations by the many communities that call this region home. However, these beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. These risks vary in type and magnitude from place to place, and while some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerously high temperatures—often accompanied by high humidity—and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available, and economic situations. In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from projected climate changes in the United States. According to the article, "[b]ecause losses are largest in regions that are already poorer on average, climate change tends to increase preexisting inequality in the United States."[11] Understanding the demographic and socioeconomic composition of racial and ethnic groups in the region is important, because these characteristics are associated with health risk factors, disease prevalence, and access to care, which in turn may influence the degree of impact from climate-related threats.

Historical Climate and Possible Future Climates

The Southeast region experienced high annual average temperatures in the 1920s and 1930s, followed by cooler temperatures until the 1970s. Since then, annual average temperatures have warmed to levels above the 1930s; the decade of the 2010s through 2017 has been warmer than any previous decade (App 5: FAQs, Figure A5.14), both for average daily maximum and average daily minimum temperature. Seasonal warming has varied. The decade of the 2010s through 2017 is the warmest in all seasons for average daily minimum temperature and in winter and spring for average daily maximum temperature. However, for average daily maximum temperature, the summers of the 1930s and 1950s and the falls of the 1930s were warmer on average. The southeastern United States is one of the few regions in the world that has experienced little overall warming of daily maximum temperatures since 1900. The reasons for this have been the subject of much research, and hypothesized causes include both human and natural influences.[13,14,15,16,17] However, since the early 1960s, the Southeast has been warming at a similar rate as the rest of the United States (Ch.

2: Climate, Figure 2.4). During the 2010s, the number of nights with minimum temperatures greater than 75°F was nearly double the long-term average for 1901–1960 (Figure 19.1), while the length of the freeze-free season was nearly 1.5 weeks greater than any other period in the historical record (Figure 19.2). These increases were widespread across the region and can have important effects on both humans and the natural environment.[18] By contrast, the number of days above 95°F has been lower since 1960 compared to the pre-1960 period, with the highest numbers occurring in the 1930s and 1950s, both periods of severe drought (Figure 19.1). The differing trends in hot days and warm nights reflect the seasonal differences in average daily maximum and average daily minimum temperature trends.

Historical Changes in Hot Days and Warm Nights

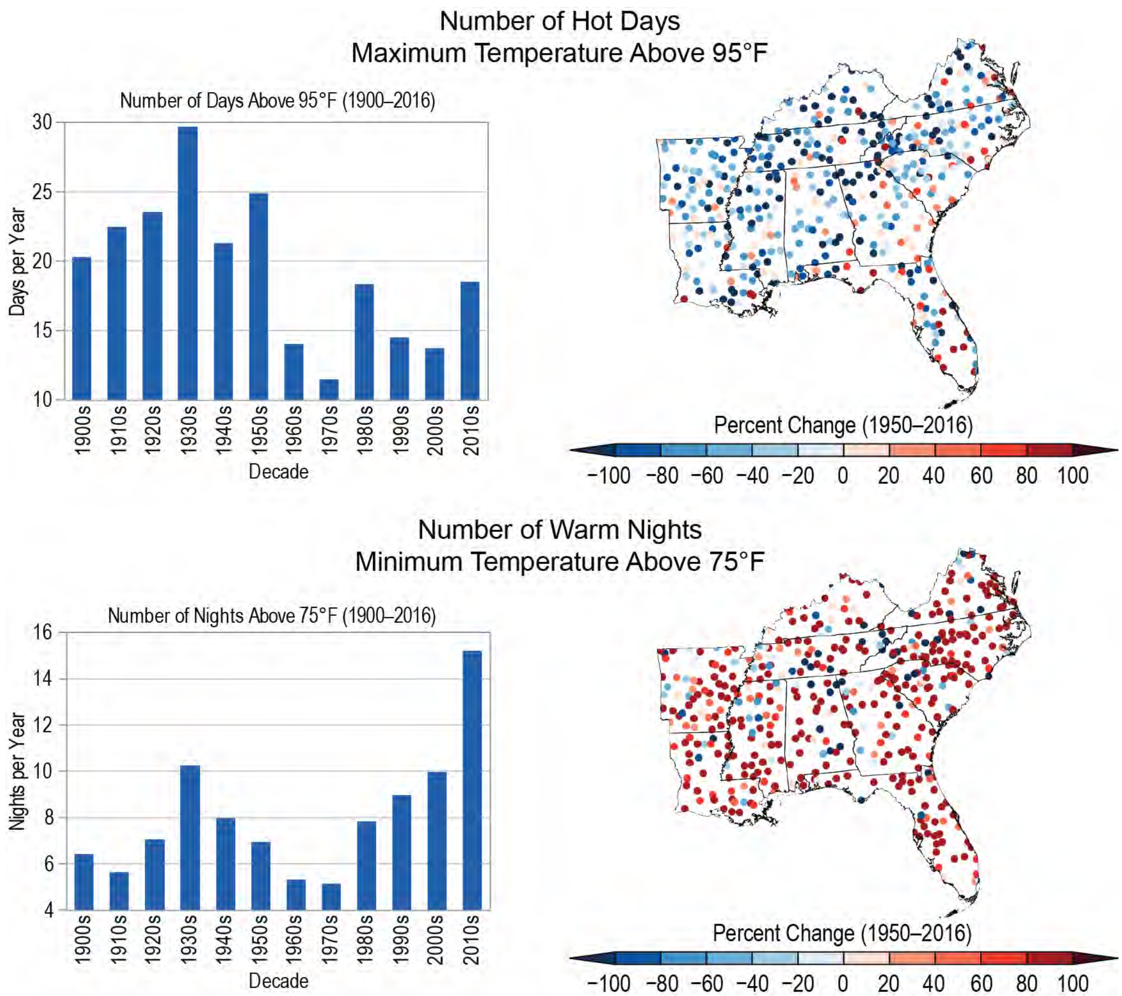


Figure 19.1: Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. Sources: NOAA NCEI and CICS-NC.

Historical Change in Freeze-Free Season Length

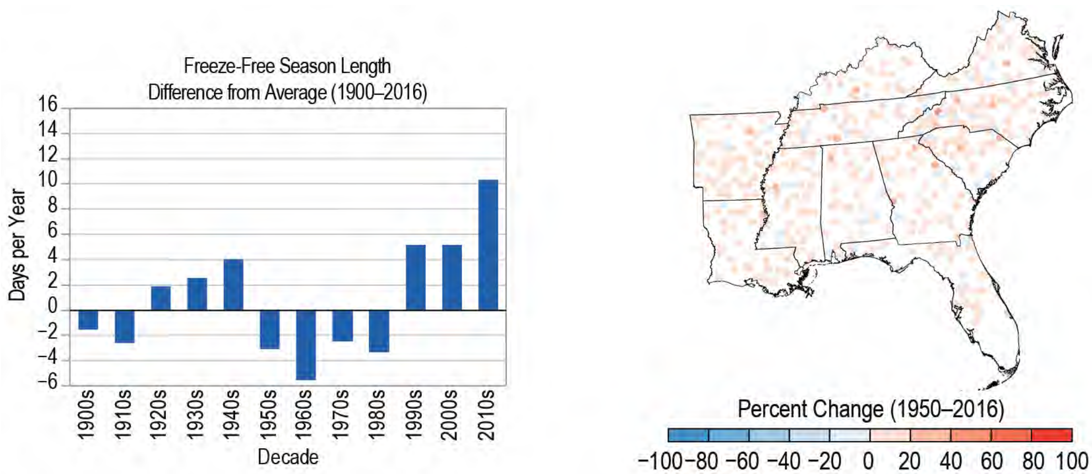


Figure 19.2: The figure shows the variability and change in the length of the freeze-free season. (left) The bar chart shows differences in the length of the freeze-free season by decade (1900–2016) as compared to the long-term average for the Southeast. (right) The map shows trends over 1950–2016 for individual weather stations. The length of the freeze-free season has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

Historical Change in Heavy Precipitation

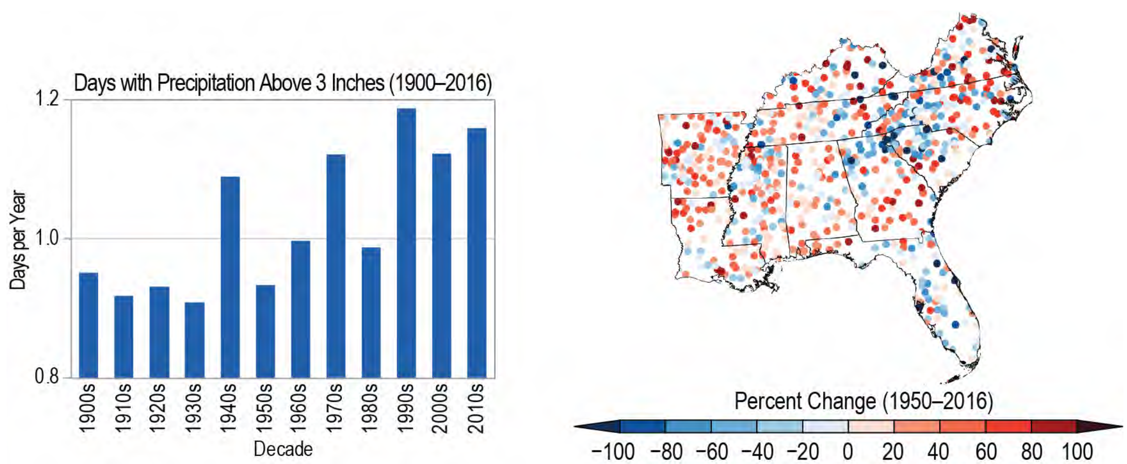


Figure 19.3: The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The numbers of days with heavy precipitation has increased at most stations,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

The number of extreme rainfall events is increasing. For example, the number of days with 3 or more inches of precipitation has been historically high over the past 25 years, with the 1990s, 2000s, and 2010s ranking as the decades with the 1st, 3rd, and 2nd highest number of events, respectively (Figure 19.3). More than 70% of precipitation recording locations show upward trends since 1950, although there are downward trends at many stations along and southeast of the Appalachian Mountains and in Florida (Figure 19.3).

Climate model simulations of future conditions project increases in temperature and extreme precipitation for both lower and higher scenarios (RCP4.5 and RCP8.5; see Figure 19.5).[13,19] After the middle of the 21st century, however, the projected increases are lower for the lower scenario (RCP4.5). Much larger changes are simulated by the late 21st century under the higher scenario (RCP8.5), which most closely tracks with our current consumption of fossil fuels. Under the higher scenario, nighttime minimum temperatures above 75°F and daytime maximum temperatures above 95°F become the summer norm and nights above 80°F and days above 100°F, now relatively rare occurrences, become commonplace. Cooling degree days (a measure of the need for air conditioning [cooling] based on daily average temperatures rising above a standard temperature—often 65°F) nearly double, while heating degree days (a measure of the need for heating) decrease by over a third (Figure 19.22). The freeze-free season lengthens by more than a month, and the frequency of freezing temperatures decreases substantially.[20,21]

Key Message 1

Urban Infrastructure and Health Risks

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

Rapid Population Shifts and Climate Impacts on Urban Areas

While the Southeast is historically known for having a rural nature, a drastic shift toward a more urbanized region is underway. The Southeast contains many of the fastest-growing urban areas in the country, including a dozen of the top 20 fastest-growing metropolitan areas (by percentage) in 2016.[22] Metropolitan Atlanta has been swiftly growing, adding 69,200 residents in just one year.[23] At the same time, many rural counties in the South are losing population.[24] These trends towards a more urbanized and dense Southeast are expected to continue, creating new climate vulnerabilities but also opportunities to adapt as capacity and resources increase in cities (Ch. 17: Complex Systems). In particular, coastal cities in the Southeast face multiple climate risks, and many planning efforts are underway in these cities. Adaptation, mitigation, and planning efforts are emphasizing "co-benefits" (positive benefits related to the reduction of greenhouse gases or implementation of adaptation efforts) to help boost the economy while protecting people and infrastructure.

Increasing Heat

Cities across the Southeast are experiencing more and longer summer heat waves. Nationally, there are only five large cities that have increasing trends exceeding the national average for all aspects of heat waves (timing, frequency, intensity, and duration), and three of these cities are in the Southeast region—Birmingham, New Orleans, and Raleigh. Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] The urban heat island effect (cities that are warmer than surrounding rural areas, especially at night) adds to the impact of heat waves in cities (Ch. 5: Land Changes, KM 1). Southeastern cities including Memphis and Raleigh have a particularly high future heat risk.[25]

The number of days with high minimum temperatures (nighttime temperatures that stay above 75°F) has been increasing across the Southeast (Figure 19.1), and this trend is projected to intensify, with some areas experiencing more than 100 additional warm nights per year by the end of the century (Figures 19.4 and 19.5). Exposure to high nighttime minimum temperatures reduces the ability of some people to recover from high daytime temperatures, resulting in heat-related illness and death.[26] This effect is particularly pronounced in cities, many of which have urban heat islands that already cause elevated nighttime temperatures.[27] Cities are taking steps to prevent negative health impacts from heat. For example, the Louisville, Kentucky, metro government conducted an urban heat management study and installed 145,000 square feet of cool roofs as part of their goal to lessen the risk of climate change impacts.[28]

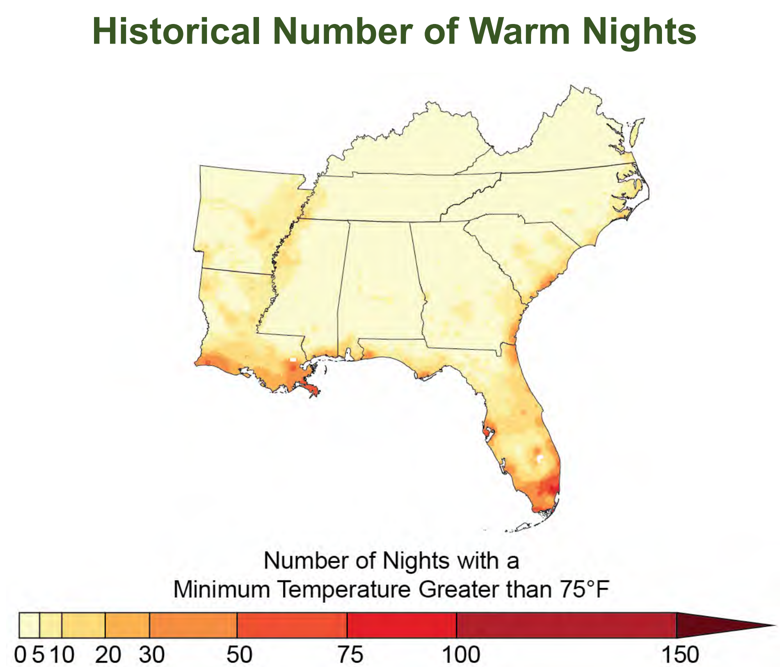


Figure 19.4: The map shows the historical number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast, based on model simulations averaged over the period 1976–2005. Sources: NOAA NCEI and CICS-NC.

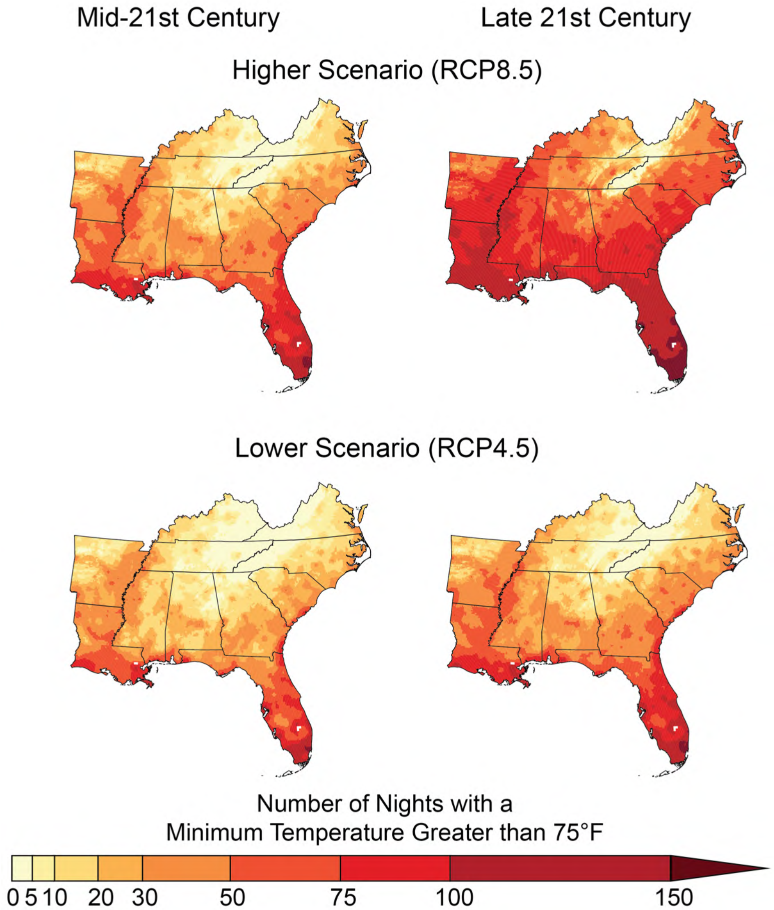


Figure 19.5: The maps show the projected number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast for the mid-21st century (left; 2036–2065) and the late 21st century (right; 2070–2099) under a higher scenario (RCP8.5; top row) and a lower scenario (RCP4.5; bottom row). These warm nights currently occur only a few times per year across most of the region (Figure 19.4) but are expected to become common events across much of the Southeast under a higher scenario. Increases in the number of warm nights adversely affect agriculture and reduce the ability of some people to recover from high daytime temperatures. With more heat waves expected, there will likely be a higher risk for more heat-related illness and deaths. Sources: NOAA NCEI and CICS-NC.

Vector-Borne Disease

The transmission of vector-borne diseases, which are spread by the bite of an animal such as a mosquito or tick, is complex and depends on a number of factors, including weather and climate, vegetation, animal host populations, and human activities (Ch. 14: Human Health, KM 1). Climate change is likely to modify the seasonality, distribution, and prevalence of vector-borne diseases in the Southeast.[29] Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors (for example, pools of standing water in man-made structures, such as tires or buckets, are breeding grounds for some species of mosquitoes). Climatic conditions are currently suitable for adult mosquitoes of the species *Aedes aegypti*, which can spread dengue, chikungunya, and Zika viruses, across most of the Southeast from July through September (Figure 19.6), and cities in South Florida already have suitable conditions for year-round mosquito activity. The Southeast is the region of the country with the most favorable conditions for this mosquito and thus faces the greatest threat from diseases the mosquito carries.[30] Climate change is expected to make conditions more suitable for transmission of certain vector-borne diseases, including year-round transmission in southern

Florida. Summer increases in dengue cases are expected across every state in the Southeast. Despite warming, low winter temperatures may prevent permanent year-round establishment of the virus across the region.[31] Strategies such as management of urban wetlands have resulted in lower dengue fever risk in Puerto Rico.[32] Similar adaptation strategies have the potential to limit vector-borne disease in southeastern cities, particularly those cities with characteristics similar to Caribbean cities that have already implemented vector control strategies (Ch. 20: U.S. Caribbean).[33,34] The Southeast is also the region with the greatest projected increase in cases of West Nile neuroinvasive disease under both a lower and higher scenario (RCP4.5 and RCP8.5).[35,36]

Air Quality and Human Health

Poor air quality directly impacts human health, resulting in respiratory disease and other ailments. In the Southeast, poor air quality can result from emissions (mostly from vehicles and power plants), wildfires, and allergens such as pollen. The major urban centers in the Southeast are already impacted by poor air quality during warmer months. The Southeast has more days with stagnant air masses than other regions of the country (40% of summer days) and higher levels of fine (small) particulate matter ($PM_{2.5}$), which cause heart and lung disease.[37] There is mixed evidence on the future health impacts of these pollutants. Ozone concentrations would be expected to increase under higher temperatures; however, a variety of factors complicate projections (Ch. 13: Air Quality, KM 1). There are many possible future wind and cloud cover conditions for the Southeast as well as the potential for continued shifts in land-use patterns, demographics and population geography, and vehicle and power plant emissions standards. Increases in precipitation and shifts in wind trajectories may reduce future health impacts of ground level ozone in the Southeast,[35] but warmer and drier

Potential Abundance of Disease-Carrying Mosquito

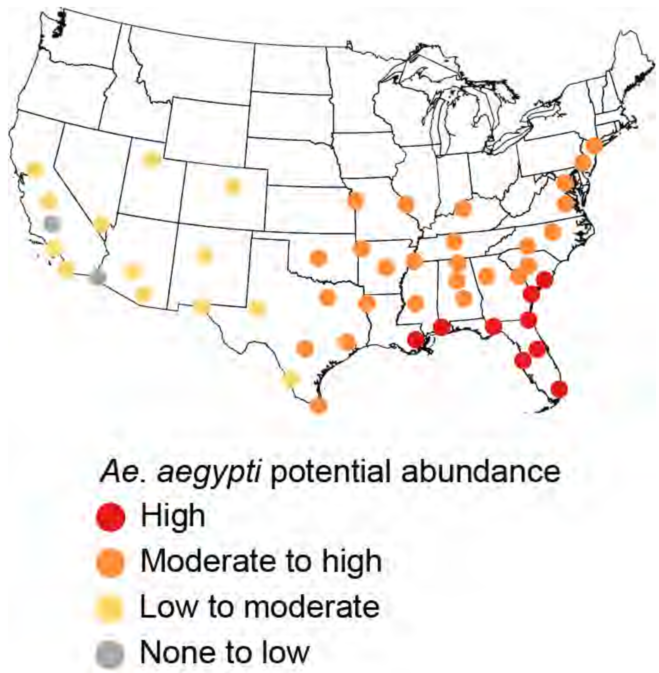


Figure 19.6: The map shows current suitability for the *Aedes aegypti* mosquito in July in 50 different cities. *Aedes aegypti* mosquitoes can spread several important diseases, including dengue fever, chikungunya, and Zika fever. The Southeast is the region of the country with the greatest potential mosquito activity. Warming temperatures have the potential to expand mosquito habitat and disease risk. Source: adapted from Monaghan et al. 2016.[30]

autumns are expected to result in a lengthening of the period of ozone exposure.[38] Warmer August temperatures in the Southeast from 1988 to 2011 were associated with increased human sensitivity to ground-level ozone.[39]

The fast growth rate of urban areas in the Southeast contributes to aeroallergens, which are known to cause and exacerbate respiratory diseases such as asthma. Urban areas have higher concentrations of CO_2, which causes allergenic plants, such as ragweed, to grow faster and produce more pollen than in rural areas.[40] Continued rising temperatures and atmospheric CO_2 levels are projected to further contribute to aeroallergens in cities (Ch. 13: Air Quality, KM 3).

Infrastructure

Infrastructure, particularly roads, bridges, coastal properties, and urban drainage, is vulnerable to climate change and climate-related events (see Key Message 2) (see also Ch. 3: Water, KM 2; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1).[41] By 2050, the Southeast is the region expected to have the most vulnerable bridges.[35] An extreme weather vulnerability assessment conducted by the Tennessee Department of Transportation found that the urban areas of Memphis and Nashville had the most at-risk transportation infrastructure in the state.[42] Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, especially in Memphis, which will likely have cascading effects across the region.[43] Transit infrastructure, such as the rail lines of the Metropolitan Atlanta Rapid Transit Authority (MARTA), are also at risk. As a result, MARTA has begun to identify vulnerable assets and prioritize improvements to develop a more resilient system.[44]

Many cities across the Southeast are planning for the impacts sea level rise is likely to have on their infrastructure (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting" and Key Message 2). Flood events in Charleston, South Carolina, have been increasing, and by 2045 the city is projected to face nearly 180 tidal floods (flooding in coastal areas at high tide) per year, as compared to 11 floods per year in 2014.[45] These floods affect tourism, transportation, and the economy as a whole. The city has responded by making physical modifications, developing a more robust disaster response plan, and improving planning and monitoring prior to flood events.

Infrastructure related to drinking water treatment and wastewater treatment may be compromised by climate-related events (Ch. 3: Water, KM 2). Water utilities across the Southeast are preparing for these impacts. Tampa Bay Water, the largest wholesale water utility in the Southeast, is coordinating with groups including the Florida Water and Climate Alliance to study the impact of climate change on its ability to provide clean water in the future.[46,47] Spartanburg Water, in South Carolina, is reinforcing the ability of the utility to "cope with, and recover from disruption, trends and variability in order to maintain services."[48] Similarly, the Seminole Tribe of Florida, which provides drinking and wastewater services, assessed flooding and sea level rise threats to their water infrastructure and developed potential adaptation measures.[49] The development of "green" water infrastructure (using natural hydrologic features to manage water and provide environmental and community benefits), such as the strategies promoted in the City of Atlanta Climate Action Plan, is one way to adapt to future water management needs. Implementation of these strategies has already resulted in a reduction in water consumption in the city of Atlanta, relieving strain on the water utility and increasing resilience.[50]

There are still gaps in knowledge regarding the potential effects of climate change on cities across the Southeast. Cross-disciplinary groups such as the Georgia Climate Project (http://www.georgiaclimateproject.org) are developing research roadmaps that can help to prioritize research and action with relevance to policymakers, practitioners, and scientists.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

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

Sea Level Rise Is Contributing to Increased Coastal Flooding in the Southeast

Average global sea level (or global mean sea level; GMSL) has risen about 8–9 inches since 1880, with about 3 inches of that rise occurring since 1990.[51,52] This recent increase in the rate of rise is projected to accelerate in the future due to continuing temperature increases and additional melting of land ice.[51] This recent global rate increase, combined with the local effects of vertical land motion (sinking) and oceanographic effects such as changing ocean currents, has caused some areas in the Southeast to experience even higher local rates of sea level rise than the global average.[53,54,55,56,57,58,59] Analyses at National Oceanic and Atmospheric Administration (NOAA) tide gauges show as much as 1 to 3 feet of local relative sea level rise in the past 100 years in low-lying areas of the Southeast.[54,59] This recent rise in local relative sea level has caused normal high tides to reach critical levels that result in flooding in many coastal areas in the region.

Monthly and seasonal fluctuations in high tide levels are caused by a combination of astronomical factors (sun and moon gravitational attraction) and non-astronomical factors such as geomorphology (landscape of the area), as well as meteorological (weather) conditions. The highest tides of the year are generally the perigean, or spring, tides, which occur when the moon is full or new and is closest to the Earth. These perigean tides, also known as "king tides," occur twice a year and in many cities are causing what has been called "nuisance" or "recurrent" flooding (referred to herein as high tide flooding). These floods can cause problems ranging from inconvenient to life changing. While the challenges brought on by rising perigean tides are diverse, important examples include increasingly frequent road closures, excessive water in storm water management systems, and deterioration of infrastructure such as roads and rail from saltwater. NOAA's National Weather Service (NWS) issues coastal flood advisories and warnings when water levels at tide gauges are expected to exceed flood thresholds. These thresholds correspond to discrete water levels relative to NOAA tide gauges.

Recent analyses of historical water levels at many NOAA tide gauges has shown an increase in the number of times that these warning thresholds were exceeded compared to the past. Annual occurrences of high tide coastal flooding have increased 5- to 10-fold since the 1960s in several low-lying coastal cities in the Southeast (Figure 19.7).[51,60] In 2015, several Southeast coastal cities experienced all-time records of coastal flooding occurrences, including Wilmington, NC (90 days), Charleston, SC (38 days), Mayport, FL (19 days), Miami, FL (18 days), Key West, FL (14 days), and Fernandina Beach, FL (7 days). These flooding occurrences increased more than 50% in 2015 compared to 2014.[58] In 2016, three all-time records were either tied (14 days at Key West, FL) or broken (50 days at Charleston, SC, and 38 days at Savannah, GA). The Miami area nearly matched the 2015 record of 18 days.[61] This increase in high tide flooding frequency is directly tied to sea level rise. For example, in Norfolk, Virginia, local relative sea level rise has led to a fourfold increase in the probability of exceeding NWS thresholds compared to the 1960s (Figure 19.8). High tide flooding is now posing daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the Southeast.[1,2]

Global sea level is very likely to rise by 0.3–0.6 feet by 2030, 0.5–1.2 feet by 2050, and 1.0–4.3 feet by 2100 under a range of scenarios from very low (RCP2.6) to high (RCP8.5),[51,52,62] which would result in increases in both the depth and frequency of coastal flooding (Figure 19.7).[51] Under higher emissions scenarios (RCP8.5), global sea level rise exceeding 8 feet (and even higher in the Southeast) by 2100 cannot be ruled out.[51] By 2050, many Southeast cities are projected to experience more than 30 days of high tide flooding regardless of scenario.[63] In addition, more extreme coastal flood events are also projected to increase in frequency and duration.[60] For example, water levels that currently have a 1% chance of occurring each year (known as a 100-year event) will be more frequent with sea level rise. This increase in flood frequency suggests the need to consider revising flood study techniques and standards that are currently used to design and build coastal infrastructure.

Higher sea levels will cause the storm surges from tropical storms to travel farther inland than in the past, impacting more coastal properties. The combined impacts of sea level rise and storm surge in the Southeast have the potential to cost up to $60 billion each year in 2050 and up to $99 billion in 2090 under a higher scenario (RCP8.5).[35] Even under a lower scenario (RCP4.5), projected damages are $56 and $79 billion in 2050 and 2090, respectively (in 2015 dollars, undiscounted).[35] Florida alone is estimated to have a 1-in-20 chance of having more than $346 billion (in 2011 dollars) in property value (8.7%) below average sea level by 2100 under a higher scenario (RCP8.5).[64] An assessment by the Florida Department of Health determined that 590,000 people in South Florida face “extreme” or “high” risk from sea level rise, with 125,000 people living in these areas identified as socially vulnerable and 55,000 classified as medically vulnerable.[65] In addition to causing direct injury, storm surge and related flooding can impact transportation infrastructure by blocking or flooding roads and affecting access to healthcare facilities (Ch. 12: Transportation, KM 1). Marine transportation can be impacted as well. Large ports in the Southeast, such as Charleston, Savannah, and Jacksonville, and the rails and roads that link to them, are particularly vulnerable to both coastal flooding and sea level rise (Ch. 12: Transportation, KM 1; Ch. 8: Coastal, KM 1). The Port of Jacksonville provides raw material for industries, food, clothes, and essential goods to Puerto Rico, thus impacting the U.S. Caribbean region, as well (Ch. 20: U.S. Caribbean, KM 3). It is estimated that with a meter (about 3.3 feet) of sea level rise, the Southeast would lose over 13,000 recorded historic and prehistoric archaeological sites and more than 1,000 locations currently eligible for inclusion on the National Register of Historic Places.[66] This includes many historic buildings and forts in cities like Charleston, Savannah, and St. Augustine.

Annual Number of High Tide Flooding Days

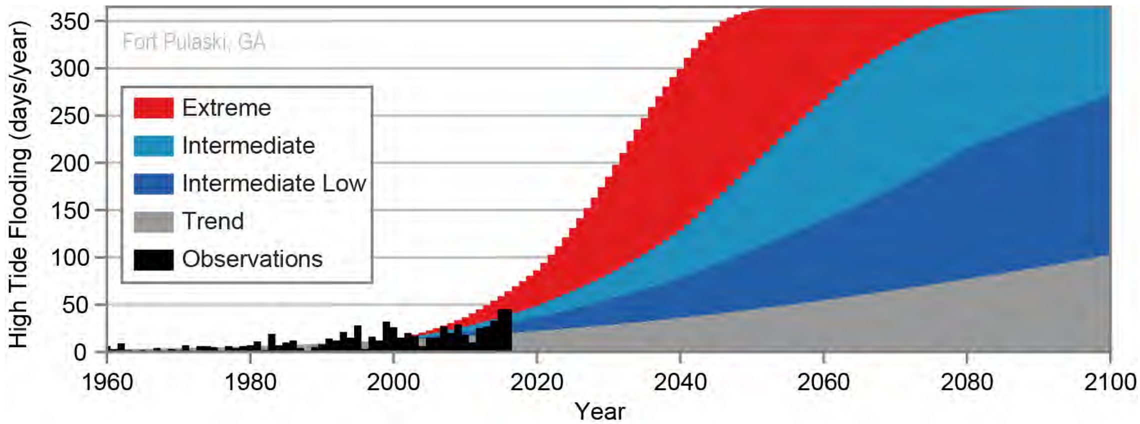


Figure 19.7: The figure shows the annual number of days experiencing high tide floods based on observations for 1960–2016 for Fort Pulaski, near Savannah, Georgia (black), and projected increases in the number of annual flood events based on four future scenarios: a continuation of the current relative sea level trend (gray) and the Intermediate-Low (dark blue), Intermediate (light blue), and Extreme (red) sea level rise scenarios. See Sweet et al. (2017)[51] and Appendix 3: Data & Scenarios for additional information on projection and trend data. Source: adapted from Sweet and Park 2014.[63]

Range of Daily Highest Water Levels in Norfolk, Virginia

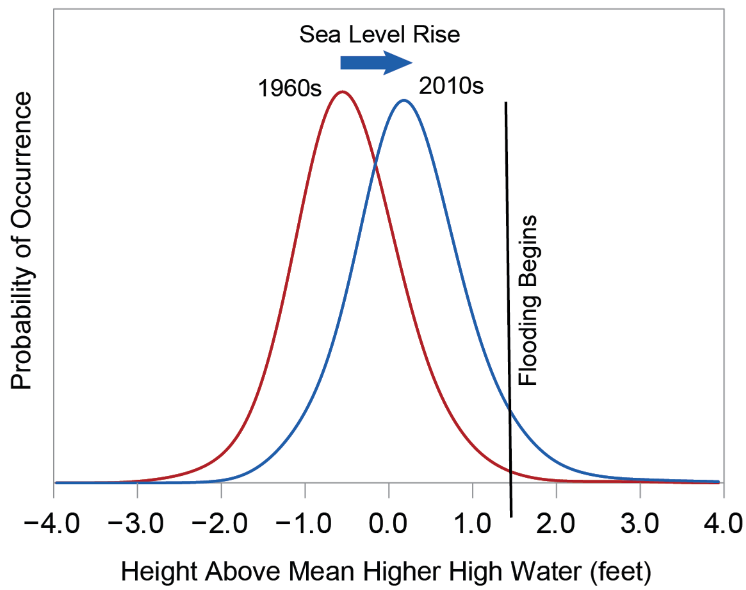


Figure 19.8: The curves in this figure show a range of daily Mean Higher High Water (MHHW) levels in Norfolk, Virginia (Sewells Point), for the 1960s and 2010s. Local sea level rise has shifted the curve closer to the point where high tide flooding begins (based on warning thresholds established by the National Weather Service). This shows why many more high tide flood events occur now than they did in the past (increase of 6 flood days per year). Source: adapted from Sweet et al. 2017.[52] *This figure was revised in June 2019. See Errata for details: https://nca2018.globalchange.gov/downloads*

Case Study: Charleston, South Carolina, Begins Planning and Reinvesting for Sea Level Rise

The main crosstown traffic artery in Charleston, South Carolina (U.S. 17 Septima Clark Parkway–crosstown), has historically been susceptible to flooding events (Figure 19.9). Charleston experienced all-time record high tide flood occurrences in 2015 (38 days) and 2016 (50 days).[52,58] By 2045, Charleston is projected to experience up to 180 high tide flood events a year.[1] The City of Charleston estimated that each flood event that affects the crosstown costs $12.4 million (in 2009 dollars). Over the past 50 years, the resultant gross damage and lost wages have totaled more than $1.53 billion (dollar year not specified). As a result, Charleston has developed a Sea Level Rise Strategy that plans for 50 years out based on moderate sea level rise scenarios (Figure 19.10) and that reinvests in infrastructure, develops a response plan, and increases readiness.[45] As of 2016, the City of Charleston has spent or set aside $235 million (in 2015 dollars) to complete ongoing drainage improvement projects (Figure 19.9) to prevent current and future flooding.

Figure 19.9: (left) U.S. Highway 17 (Septima Clark Parkway—crosstown) in Charleston, South Carolina, during a flood event. Floodwaters can get deep enough to stall vehicles. (right) Market Street drainage tunnel being constructed in Charleston, South Carolina, as part of a drainage improvement project to prevent current and future flooding. This tunnel crosses a portion of downtown Charleston 140 feet underground and is designed to rapidly convey storm water to the nearby Ashley River. Photo credit: City of Charleston 2015.[45]

Projected Sea Level Rise for Charleston, South Carolina

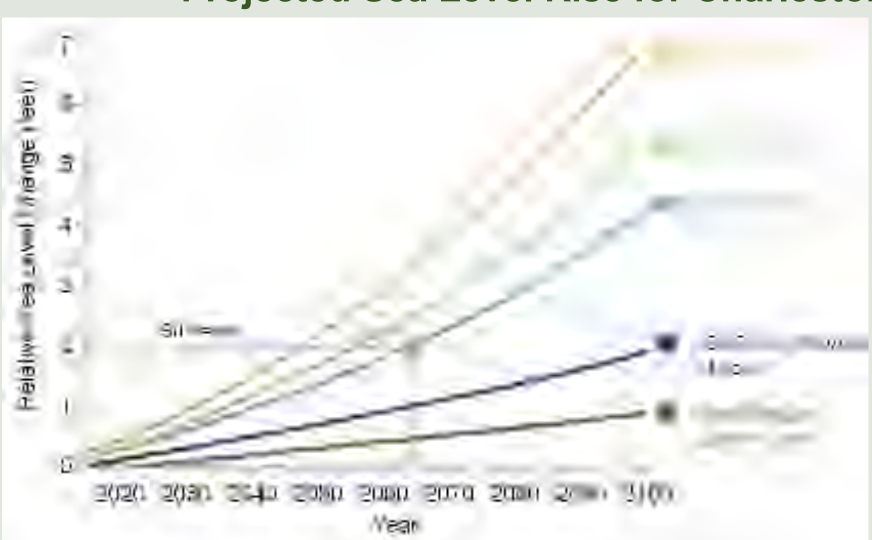


Figure 19.10: The City of Charleston Sea Level Rise Strategy calls for a 50-year outlook, based on existing federal sea level change projections in 2015 (colored curves), and calls for using a range of 1.5–2.5 feet of sea level rise (dashed box). A 1.5-foot increase will be used for short-term, less vulnerable investments, such as a parking lot. A 2.5-foot increase will be used for critical, longer-term investments, such as emergency routes and public buildings. This 1-foot range was chosen to approximate the average of these projections in 2065. Source: City of Charleston 2015.[45]

Many of the older historical coastal cities in the Southeast were built just above the current Mean Higher High Water (MHHW) level (the average height of the higher of the two daily high tides at a given location), with a gravity-driven drainage system designed to drain rainwater into the tidal estuaries. As sea levels have risen locally in the last one hundred years, the storm water systems in these areas are no longer able to perform as designed. When these cities experience high tide coastal flooding due to perigean tides, the tidewater enters the storm water system, which prevents rainwater from entering storm drains and causes increased impacts from flooding. In the future, the gravity-driven nature of many of these systems may cease to function as designed, causing rainwater to flood streets and neighborhoods until the tide lowers and water can drain normally. Cities such as Charleston and Miami have already begun to improve storm water infrastructure and explore natural and nature-based infrastructure design to reduce future flood risk.

Much of the Southeast region's coast is bordered by large expanses of salt marsh and barrier islands. Long causeways with intermittent bridges to connect the mainland to these popular tourism destinations were built decades ago at only a few feet above MHHW. Sea level rise has put these transportation connection points at risk. High tide coastal flooding has started to inundate these low-lying roads, restricting access during certain times of the day and causing public safety concerns. The U.S. East Coast, for example, already has 7,508 miles of roadways, including over 400 miles of interstate roadways, currently threatened by high tide coastal flooding (Ch. 12: Transportation, KM 1 and Figure 12.2).

Sea level rise is already causing an increase in high tide flood events in the Southeast region and is adding to the impact of more extreme coastal flooding events. In the future, this flooding is projected to become more serious, disruptive, and costly as its frequency, depth, and inland extent grow with time (Ch. 12: Transportation, KM 1).[52,63,67,68]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe

Coastal communities in the Southeast are already experiencing impacts from higher temperatures, sea level rise, increased flooding, and extreme weather events.[69,70,71,72] Several communities in the United States are already discussing the complexities of relocation; most are tribal and Indigenous communities.[73] Some have chosen to stay in their homelands, while others have few options but to relocate (Ch. 15: Tribes, KM 3).

Isle de Jean Charles is a narrow island in the bayous of South Terrebonne Parish, Louisiana, and home to the Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw, a tribal community already living the day-to-day impacts of land loss, sea level rise, and coastal flooding. The island has lost 98% of its landmass since 1955 and has only approximately 320 acres (approximately 1/2 square mile) remaining. The population living on the Island has fallen from 400 to 85 people. The decline is due in large part to land loss and flooding driven by climate change, extreme weather, and unsustainable development practices, which stem from oil and gas production, extraction, and water-management practices.[74] This process has resulted in family separation, spreading them across southern Louisiana.[75] In addition, the Tribe continues to lose parts of its livelihood and culture, including sacred places, cultural sites and practices, healing plants, traditional foods, and lifeways.[76]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe, *continued*

The Third National Climate Assessment[77] discussed the initial plans for resettlement of the Isle de Jean Charles community. Recently, after nearly 20 years of tribal persistence and two previous efforts, the U.S. Department of Housing and Urban Development (HUD) through the National Disaster Resilience Competition,[78] along with technical assistance from The Rockefeller Foundation, awarded the State of Louisiana $48 million (in 2016 dollars) to implement the Tribe's resettlement plan: a community-driven, culturally appropriate, sustainable development-based plan. It was developed in partnership with the Lowlander Center, a local nongovernmental organization with a long-standing relationship with the Tribe and other scientists, researchers, and planners. The award provides the Tribe with a historic opportunity to reunite a community.[79] While the application to relocate was initiated by the Tribe, the relocation funds now are for all residents of Isle de Jean Charles, according to the Louisiana State Office of Community Development.[75]

Figure 19.11: Chantel Comardelle, Isle de Jean Charles Tribe's Executive Secretary, leads a discussion at a community meeting for the Tribe's resettlement planning process in Pointe-aux-Chenes, Louisiana, on January 18, 2016. The meeting was supported by the Lowlander Center. Photo credit: The Lowlander Center Team.

The resettlement plan is expected to be implemented by 2022 with the inclusion of many facilities in the new location to revitalize the tribal community, including a tribal center and a healthcare facility. The Tribe's experience highlights how success can be achieved when at-risk communities are engaged in the resettlement planning process from the beginning to ensure long-term successful relocation and maintain community integrity.[80] It also highlights an opportunity for institutions to evolve in more flexible ways to accommodate the growing number of communities that may need to relocate.

Extreme Rainfall Events Are Contributing to Increased Inland and Coastal Flooding

Extreme rainfall events have increased in frequency and intensity in the Southeast, and there is *high confidence* they will continue to increase in the future (Figure 19.3).[19] The region, as a whole, has experienced increases in the number of days with more than 3 inches of precipitation (Figure 19.3) and a 16% increase in observed 5-year maximum daily precipitation (the amount falling in an event expected to occur only once every 5 years).[19] Both the frequency and severity of extreme precipitation events are projected to continue increasing in the region under both lower and higher scenarios (RCP4.5 and RCP8.5). By the end of the century under a higher scenario (RCP8.5), projections indicate approximately double the number of heavy rainfall events (2-day precipitation events with a 5-year return period) and a 21% increase in the amount of rain falling on the heaviest precipitation days (days with a 20-year return period).[19,81] These projected increases would directly affect the vulnerability of the Southeast's coastal and low-lying areas. Natural resources (see Key Message 3), industry, the local economy, and the population of the region are at increasing risk to these extreme events.

Across the Southeast since 2014, there have been numerous examples of intense rainfall events—many approaching levels that would be expected to occur only once every 500 years[82,83]—that have made state or national news due to the devastating impact they had on inland communities. Of these events, four major inland flood events have occurred in just three years (2014–2016) in the Southeast, causing billions of dollars in damages and loss of life (see Table 19.1 and Case Study “Coastal and Inland Impacts of Extreme Rainfall”).[84]

A closer look at the August 2016 event in Louisiana provides an example of how vulnerable inland communities in the Southeast region are to these extreme rainfall events. Between August 11–15 2016, nearly half of southern Louisiana received at least 12–14 inches of rainfall. While urban areas such as Baton Rouge and Lafayette were hit the hardest, receiving upwards of 30 inches in a few days, coastal locations were also inundated with up to 20 inches of rain. Rainfall totals across the region exceeded amounts that would be expected to occur once every 1,000 years (or a less than 0.1% annual probability of occurrence), causing the Amite and Comite Rivers to surge past their banks and resulting in some 50,000 homes across the region filling with more than 18 inches of water.[85] Nearly 10 times the number of homes received major flooding (18 inches or more) during this event compared to a historic 1983 flood in Baton Rouge, and the damage resulted in more than 2 million cubic yards of curbside debris from cleaning up homes (enough to fill over 600 Olympic-sized pools).[86] A preceding event in northern Louisiana on March 8–12, 2016, caused $2.4 billion in damages (in 2017 dollars; $2.3 billion in 2015 dollars) and five casualties,[84] illustrating that inland low-lying areas in the Southeast region are also vulnerable to flooding impacts. Events of such magnitudes are projected to become more likely in the future due to a changing climate,[19,87] putting more people in peril from future floods. Existing flood map boundaries do not account for future flood risk due to the increasing frequency of more intense precipitation events, as well as new development that would reduce the floodplain’s ability to manage storm water. As building and rebuilding in flood-prone areas continue, the risks of the kinds of major losses seen in these events will continue to grow.

The growing number of extreme rainfall events is stressing the deteriorating infrastructure in the Southeast. Many transportation and storm water systems have not been designed to withstand these events. The combined effects of rising numbers of high tide flooding and extreme rainfall events, along with deteriorating storm water infrastructure, are increasing the frequency and magnitude of coastal and lowland flood events.[45,88,89,90]

Billion-Dollar Flood Events in the Southeast, 2014–2016

Event	Date	Damages	Casualties
Southeast tornadoes and flooding (FL, AL, AR)	April 27–28, 2014	$1.8 Billion	33
South Carolina record flooding	October 1–5, 2015	$2.1 Billion	25
Hurricane Matthew	October 7–9, 2016	$10.1 Billion	49
Louisiana flooding (Baton Rouge)	August 11–15, 2016	$10.1 Billion	13

Table 19.1: Values are Consumer Price Index adjusted and are in 2017 dollars. Source: NOAA NCEI 2017.[84]

The recent increases in flood risk have led many cities and counties to take adaptive actions to reduce these effects. Four counties in Southeast Florida formed a climate compact in 2010 to address climate change impacts, including sea level rise and high tide flooding.[91] Recently updated in 2017, their climate action plan was one of the first intergovernmental collaborations to address climate change, adaptation, and mitigation in the country. Since then, cities like Charleston, South Carolina, have started to invest in flood management activities (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting"). Other examples include Miami Beach, Florida, which has a multiyear, $500-million program to raise public roads and seawalls and improve storm water drainage.[92] Norfolk, Virginia, has begun comprehensive planning to fix its high tide flooding issues.[93] Biloxi, Mississippi, has put in place several adaptation strategies to lessen the future impacts, including enacting a new building code that requires elevating structures an additional one foot above the base flood elevation.[94] Tybee Island, Georgia, has developed a sea level rise adaptation plan with recommendations to flood-proof a 5.5-mile stretch of their sole access causeway, replace two vulnerable bridges, and retrofit their existing storm water infrastructure to improve drainage.[95] In response to the 2016 flooding, eight parishes in the Acadiana region of Louisiana came together to collaborate at a watershed level, pooling their federal hazard mitigation grant funding to support projects across the Teche-Vermilion watershed. This is the only watershed-level hazard mitigation collaboration of this kind happening in the state and has the support of the Federal Emergency Management Agency (FEMA), the Governor's Office of Homeland Security and Emergency Preparedness, and the Louisiana Office of Community Development.[96]

Many communities in the Southeast also participate in FEMA's Community Rating System (CRS) program, which provides reduced flood insurance premiums to communities that go above and beyond the minimum National Flood Insurance Program regulation standards.[97] Many communities require a safety factor, also known as freeboard, expressed as feet above the base flood elevation, for construction in special flood hazard areas. Several Southeast communities—such as Hillsborough and Pinellas Counties, Florida; Biloxi, Mississippi; Chatham County, Georgia; and Myrtle Beach, South Carolina—have earned low CRS classes (5 on a scale of 1–10, with 1 being the best or most insurance premium discount) by implementing freeboard and other regulations that exceed the minimum standards.[97]

Case Study: Coastal and Inland Impacts of Extreme Rainfall

In October 2015, an extreme rainfall event impacted both inland and coastal South Carolina, leading to the largest flood-related disaster in the state since Hurricane Hugo struck in 1989. The October 2015 event is among a series of devastating precipitation events that have occurred across the Southeast in recent years. From October 1–5, 2015, deep tropical moisture combined with a slow-moving (stalled) upper-level low pressure system to pump moisture into South Carolina's coastal and interior regions. Much of the affected region received between 10 and 26 inches of rain over the 4-day event, breaking many all-time precipitation records (Figure 19.12). Mount Pleasant, located on South Carolina's coast, received 26.88 inches of rain, which is an extremely rare event. The rainfall sparked inland flooding that led to three dam breaches and the destruction of countless roads and homes (see Figure 19.13 showing flash flooding impacts to inland roads). Roughly 52,000 residents applied for disaster relief, and 160,000 homes sustained some type of damage. At the coast, a combination of high tide and heavy rain caused significant flooding in downtown Charleston. A high tide of 2.38 feet above Mean Higher High Water (MHHW) occurred in the afternoon of October 3. This was the seventh highest tide ever recorded in Charleston Harbor and the highest since Hurricane Hugo in 1989. Under future climate scenarios, the combination of extreme precipitation and higher tides due to local sea level rise will likely cause more frequent events of this intensity and magnitude.[98]

Case Study: Coastal and Inland Impacts of Extreme Rainfall, *continued*

October 2015 Extreme Rainfall Event

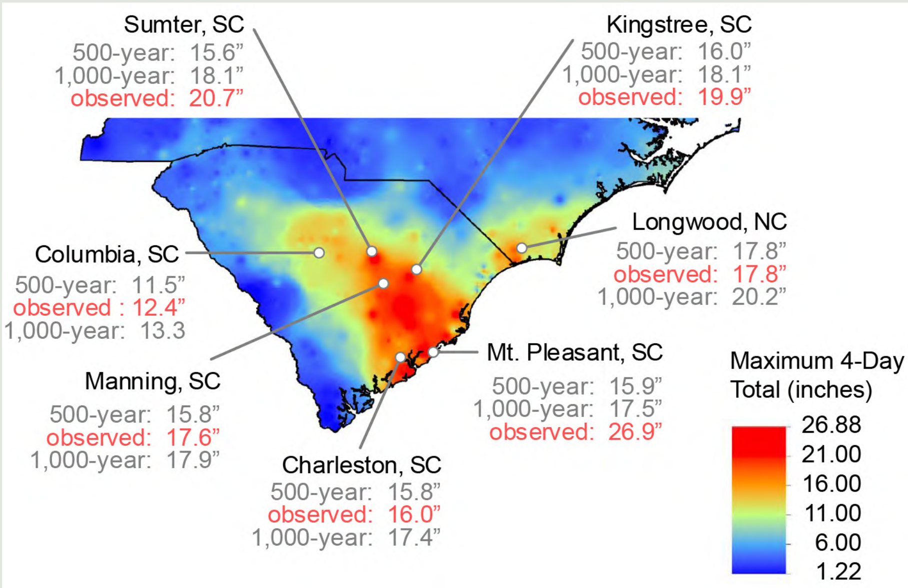


Figure 19.12: The map shows rainfall totals from the October 2015 South Carolina flood event. Red colors in the map indicate areas that received excessive rainfall totals that broke all-time records. Some of these totals exceeded the 500-year and 1,000-year return period amounts (rainfall amounts that would be expected to have only a 0.2% or 0.1% chance of occurring in a given year). Extreme precipitation events will likely increase in frequency in the Southeast. Source: CISA 2015.[98]

Figure 19.13: Many roads became impassable in the inland areas of South Carolina as a result of the October 2015 extreme rainfall event. This photo shows a neighborhood in North Charleston after the event with knee-deep flooding. Photo credit: Ryan Johnson (CC BY-SA 2.0).

Increases in extreme rainfall events and high tide coastal floods due to future climate change could impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Recent social science studies have indicated that people may migrate from many coastal communities that are vulnerable to the impacts of sea level rise, high tide flooding, saltwater intrusion, and storm surge.[71] Even though many communities are starting to develop adaptation strategies to address current flooding issues, many adaptation strategies are not being designed for longer time horizons and more extreme worst-case climate scenarios.[1,67]

The 2017 Hurricane Season

For the United States, 2017 was a historic year for weather and climate disasters, with widespread impacts and lingering costs. While 2017 tied the previous record year of 2011 for the total number of billion-dollar weather and climate disasters—16—the year broke the all-time previous record high costs by reaching $306.2 billion in damages (in 2017 dollars; $297 billion in 2015 dollars). The previous record year was 2005 with a total of $214.8 billion (in 2017 dollars; $208.4 billion in 2015 dollars), which included the impacts of Hurricanes Dennis, Katrina, Rita, and Wilma.[99]

In 2017, Hurricane Irma was one of three major hurricanes to make landfall in the United States and territories, with the most significant impacts occurring in the Southeast region. Irma was a Category 4 storm with 130 mph wind speeds when it made landfall at Cudjoe Key, Florida (20 miles north of Key West). Storm surge inundations at Cudjoe and the surrounding Keys were between 5 and 8 feet.[100] Prior to landfall in Florida, Irma caused significant damage in the U.S. Virgin Islands and parts of Puerto Rico as a Category 5 hurricane with 185 mph wind speeds (see Ch. 20: U.S. Caribbean, Box 20.1 and KM 5).[84]

Irma's intensity was impressive by any measure. According to the National Weather Service, Hurricane Irma was only the fifth hurricane with winds of 185 mph or higher in the whole of the Atlantic Basin since reliable record keeping began, and it was the strongest observed hurricane in the open Atlantic Ocean.[101] For three days, the storm maintained maximum sustained winds of 185 miles per hour, the longest observed duration in the satellite era.[101,102] Not only was Irma extremely strong, it was also very large with tropical storm force winds reaching as far away as 400 miles from the hurricane's center and driving hurricane force winds up to 80 miles away.[101] Two factors supported Irma's strength: the very warm waters it passed over, which exceeded 86°F,[102] and the light winds Irma encountered in the upper atmosphere (Figure 19.14).[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Rapid intensification of storms is also more likely as the climate warms,[104] even though there is also some historical evidence that the same conditions that lead to this intensification also act to weaken hurricane intensity near the U.S. coast, but it is unclear whether this relationship will continue as the climate warms further (see Kossin et al. 2017,[103] Box 9.1).

The storm tracked up the west coast of Florida, impacting both coasts of the Florida peninsula with 3–5 feet of inundation from Cape Canaveral north to the Florida–Georgia border and even further, impacting coastal areas of Georgia and South Carolina with high tides and storm surge that reached 3–5 feet. Inland areas were also impacted by winds and heavy rains with river gauges and high-water marks showing upwards of 2–6 feet above ground level.[100] The winds eventually fell below tropical storm strength near Columbus, Georgia. Even though the wind speed fell below tropical storm strength, many communities along the coasts of Florida, Georgia, North and South Carolina, and Virginia experienced severe wind and storm surge damage with some near-historic levels of coastal flooding. A state of emergency was declared in four states from Florida north to Virginia and in Puerto Rico and the U.S. Virgin Islands, and, for the first time ever, Atlanta was placed under a tropical storm warning.[105,106,107,108] In Florida, a record 6.8 million people were ordered to evacuate, as were 540,000 coastal residents in Georgia and untold numbers in other coastal locations.[102,109,110] Nearly 192,000 evacuees were housed in approximately 700 emergency shelters in Florida alone.[109] According to NOAA's National Centers for Environmental Information (NCEI),[84] Irma significantly damaged 65% of the buildings in the Keys and destroyed 25% of them.

Warm Waters Contribute to the Formation of Hurricane Irma

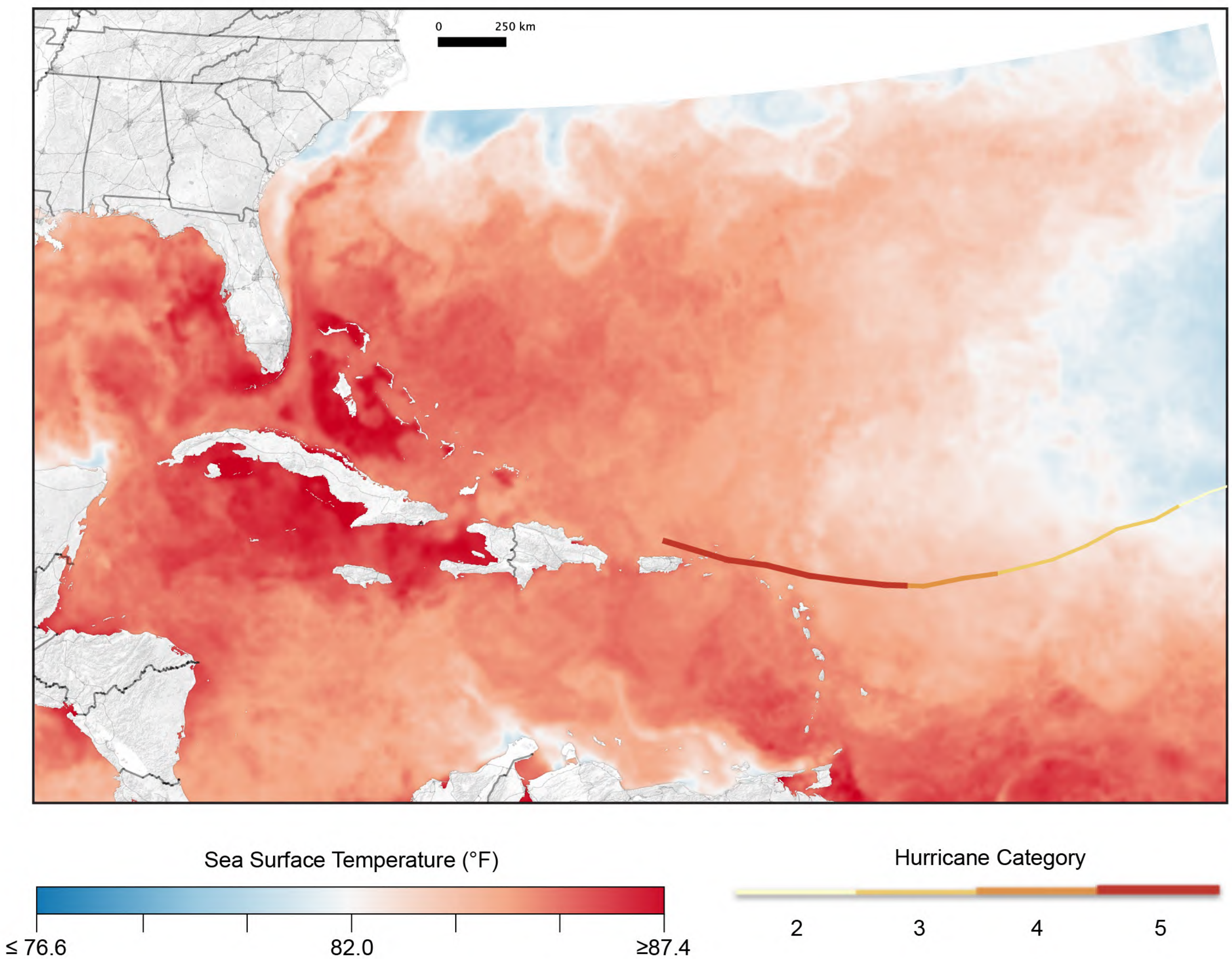


Figure 19.14: Two factors supported Hurricane Irma's strength as it reached the Southeast region: the very warm waters it passed over, depicted in this figure, and the light winds Irma encountered in the upper atmosphere.[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Source: NASA 2017.[102]

High rainfall totals were experienced in many impacted areas, with Fort Pierce, Florida, receiving the highest rainfall of more than 21.5 inches[100] and the Florida Keys receiving 12 inches of rain.[84,102] Flooding occurred on most rivers in northern Florida and in many rivers in both Georgia and South Carolina to the point that rescues were required. In Jacksonville, Florida, heavy rains were the major issue causing rivers to reach major or record flood stage and flooded some city streets up to 5 feet deep in water. The heavy rainfall was noted even in Alabama, at 5 inches, and near 6 inches in the mountains of western North Carolina.[100] Twenty-five tornadoes were confirmed from Hurricane Irma, and many of them occurred along the east coast of central and northern Florida.[100] Even as Irma headed north, continuing to lose force, there were still 6.7 million people without electricity.[109]

According to NCEI,[84] the U.S. direct cost from Hurricane Irma is approximately $50 billion (in 2017 dollars), and the non-U.S. territory Caribbean Islands could add another $10–$15 billion to that total. Of the $50 billion, approximately $30–$35 billion accounts for wind and flood damage to a combination of residential and commercial properties, automobiles, and boats—with 80%–90% of this cost felt in Florida. The remainder of the costs include $5 billion for infrastructure repairs and $1.5–$2.0 billion for damage to the agricultural sector, also mainly in Florida. The remaining costs would address losses in the U.S. Virgin Islands and Puerto Rico.[84] The losses could have been worse except for the fact that Florida has implemented one of the strictest building codes in the country after the destruction caused by Hurricane Andrew in 1992.[111] Recent estimates using insured loss data show that implementing the Florida Building Code resulted in a 72% reduction of windstorm losses, and for every $1 in added cost to implement the building code, there is a savings of $6 in reduced losses, with the return or payback period being roughly 8 years (in 2010 dollars).[111]

Indirect impacts and costs are difficult to calculate and would add to the totals. In Central and South Florida, such things would include the closing of schools, colleges, and universities; the closing of tourist attractions and the cancellation of thousands of flights into and out of region; and the closing or restricting of the use of seaports including Canaveral, Key West, Miami, and Jacksonville, among others.[109,112] The Select Committee on Hurricane Response and Preparedness: Final Report[109] estimates that there were 84 U.S. deaths attributable to Hurricane Irma and other untold damage and human suffering. While the hurricane directly damaged portions of the Southeast, the impacts could be felt around the country in the form of business interruptions (such as tourism), transportation and infrastructure damages (such as ports, roadways, and airports), increases in fuel costs, and $2.5 billion (in 2018 dollars) in total estimated crop losses,[109] which had the potential to impact the cost of food and other products for all Americans.

Key Message 3

Natural Ecosystems Will Be Transformed

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

Ecosystems in the Southeast span the transition zone between tropical and temperate climates. The region's more temperate ecosystems include hardwood forests, spruce-fir forests, pine-dominated forests, and salt marshes. The region's more tropical ecosystems include mangrove forests, coral reefs, pine savannas, and the tropical freshwater wetlands of the Everglades. Ecological diversity in the Southeast is high,[113,114,115,116,117] and southeastern ecosystems and landscapes provide many benefits to society. In addition to providing habitat for fish and wildlife species, ecosystems in the Southeast provide recreational opportunities, improve water quality, provide seafood, reduce erosion, provide timber, support food webs, minimize flooding impacts, and support high rates of carbon sequestration (or storage).[118,119,120] These ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change.

Climate greatly influences the structure and functioning of all natural systems (Ch. 7: Ecosystems). An analysis of ecological changes that have occurred in the past can help provide some context for anticipating and preparing for future ecological changes. In response to past climatic changes, many ecosystems in the Southeast were much different than those present today. For example, since the end of the last glacial maximum (about 19,000 years ago—the most recent period of maximum ice extent),[121] forests in the region have been transformed by warming temperatures, sea level rise, and glacial retreat.[122,123] Spruce species that were once present in the region's forests have moved northward and have been replaced by oaks and other less cold-tolerant tree species that have expanded from the south.[124] And along the coast, freeze-sensitive mangrove forests and other tropical coastal species have been expanding northward and upslope since the last glacial maximum.[125,126,127,128,129]

In the coming decades and centuries, climate change will continue to transform many ecosystems throughout the Southeast,[6,130,131,132,133,134,135] which would affect many of the societal benefits these ecosystems provide. As a result, future generations can expect to experience, interact with, and potentially benefit from natural systems that are much different than those that we see today (Ch. 7: Ecosystems).[136,137]

Warming Winter Temperature Extremes

Changes in winter air temperature patterns are one aspect of climate change that will play an especially important role in the Southeast. By the late 21st century under the higher scenario (RCP8.5), the freeze-free season is expected to lengthen by more than a month. Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[138,139,140,141,142,143,144] Certain ecosystems in the region are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (in other words, ecological regime shifts).[135,145] Reductions in the frequency and intensity of cold winter air temperature extremes can allow tropical and subtropical species to move northward and replace more temperate species. Where climatic thresholds are crossed, certain ecosystem and landscapes will be transformed by changing winter air temperatures.

Plant hardiness zone maps help convey the importance of winter air temperature extremes for species and natural systems in the Southeast. To help gardeners and farmers, the U.S. Department of Agriculture has produced plant hardiness zone maps that can be used to determine which species are most likely to survive and thrive in a given location. The plant hardiness zones are reflective of the frequency and intensity of winter air temperature extremes in a specific region. Already, in response to climate change, plant hardiness zones in certain areas are moving northward and are expected to continue their northward and upslope progression.[139,142,146,147] Continued reductions in the frequency and intensity of winter air temperature extremes are expected to change which species are able to survive and thrive in a given location (Figure 19.15). For example, citrus species are sensitive to freezing and chilling temperatures.[148] However, in the future, climate change is expected to enable the survival of citrus in areas that are north of the current tolerance zone.[142]

The effects of changing winters reach far beyond just agricultural and garden plants. Along the coast, for example, warmer winter temperatures are expected to allow mangrove forests to move northward and replace salt marshes (Figures 19.16 and 19.17).[135,149,150,151,152]

Coastal wetlands, like mangrove forests and salt marshes, are abundant in the Southeast.[153,154] The societal benefits provided by coastal wetlands are numerous.[119] Hence, where coastal wetlands are abundant (for example, the Mississippi River Delta), their cumulative value can be worth billions of dollars each year and trillions of dollars over a 100-year period.[155] Coastal wetlands provide seafood, improve water quality, provide recreational opportunities, reduce erosion, support food webs, minimize flooding impacts, and support high rates of carbon sequestration.[118] Foundation species are species that create habitat and support entire ecological communities.[156,157] In coastal wetlands and many other ecosystems, foundation plant species play an especially important role. Hence, the loss and/or replacement of foundation plant species, like salt marsh grasses, will have ecological and societal consequences in certain areas.[135,145,157,158,159,160,161,162,163,164]

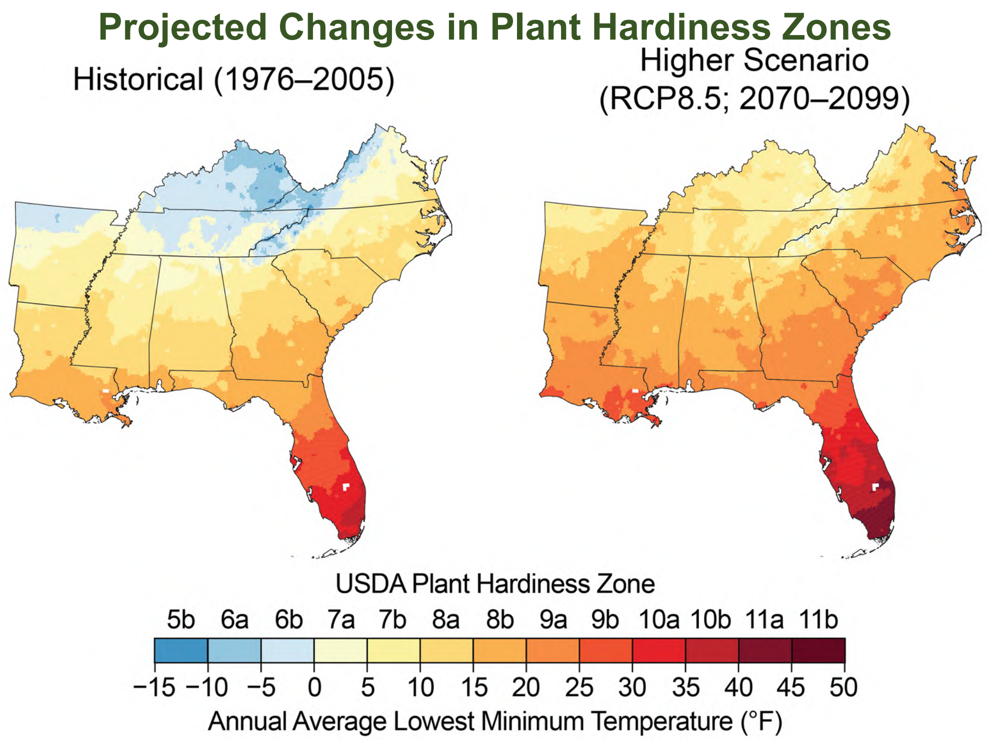


Figure 19.15: Increasing winter temperatures are expected to result in a northward shift of the zones conducive to growing various types of plants, known as plant hardiness zones. These maps show the mean projected changes in the plant hardiness zones, as defined by the U.S. Department of Agriculture (USDA), by the late 21st century (2070–2099) under a higher scenario (RCP8.5). The USDA plant hardiness zones are based on the average lowest minimum temperature for the year, divided into increments of 5°F. Based on these projected changes, freeze-sensitive plants, like oranges, papayas, and mangoes, would be able to survive in new areas.[142] Note that large changes are projected across the region, but especially in Kentucky, Tennessee, and northern Arkansas. Sources: NOAA NCEI and CICS-NC.

While salt marsh and mangrove wetlands both contain valuable foundation species, some of the habitat and societal benefits provided by existing salt marsh habitats will be affected by the northward expansion of mangrove forests.[145,158,160,161,164,165]

Salt Marsh Conversion to Mangrove Forest

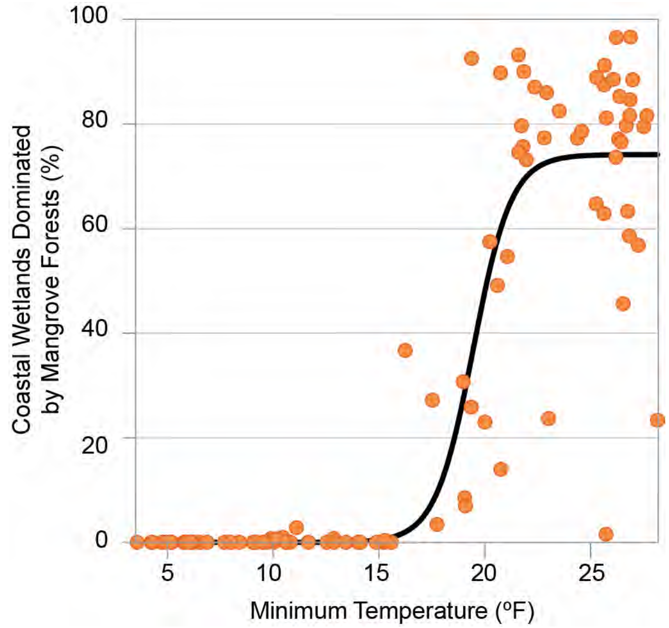


Figure 19.16: Where tropical and temperate ecosystems meet, warmer winter temperatures can lead to large ecological changes such as mangrove forest replacement of salt marshes along the Gulf and Atlantic Coasts. Mangrove forests are sensitive to freezing temperatures and are expected to expand northward at the expense of salt marshes. The figure shows the relationship between temperature and the percentage area dominated by mangrove forests. Mangrove expansion would entail a grassland-to-forest conversion, which would affect fish and wildlife habitat and many societal benefits. Source: adapted from Osland et al. 2013.[135] ©2012 Blackwell Publishing Ltd.

Transitioning Coastal Ecosystems

Figure 19.17: In Louisiana and parts of northern Florida, future coastal wetlands are expected to look and function more like the mangrove-dominated systems currently present in South Florida and the Caribbean. Like salt marshes (left), mangrove forests (right) provide coastal protection against wind and waves (Ch. 20: U.S. Caribbean, KM 2). Photo credit: Michael Osland.

In addition to plants, warmer winter air temperatures will also affect the movement and interactions between many different kinds of organisms. For example, certain insect species, including mosquitoes and tree-damaging beetles, are expected to move northward in response to climate change, which could affect human health and timber supplies.[30,144,166,167,168,169,170,171,172] And some bird species, including certain ducks, are not expected to migrate as far south in response to milder winters,[173] which could affect birding and hunting recreational opportunities. Many recreational fishery populations in tropical coastal areas are freeze-sensitive[138,174,175,176,177,178] and are, therefore, expected to move northward in response to warmer water and air temperatures. Although the appearance of tropical recreational fish, like snook for example, may be favorable for some anglers, the movement of tropical marine species is expected to greatly modify existing food webs and ecosystems (Ch. 7: Ecosystems, Figure 7.4).[179] Some problematic invasive species are expected to be favored by changing winters. For example, in South Florida, the Burmese python and the Brazilian pepper tree are two freeze-sensitive, nonnative species that have, respectively, decimated mammal populations and transformed native plant communities within Everglades National Park.[180,181,182,183,184,185,186,187,188] In the future, warmer winter temperatures are expected to facilitate the northward movement of these problematic invasive species, which would transform natural systems north of their current distribution.

Warm Winters Favor Invasive Species

Figure 19.18: Burmese pythons are apex predators (not preyed upon by other animals) that are sensitive to cold temperatures and are expected to be favored by warming winters. This photo is from Everglades National Park, where unintentionally introduced pythons have expanded and reduced native mammal populations. Photo credit: U.S. Geological Survey.

Changing Patterns of Fire

In the Southeast region, changing fire regimes (defined by factors including frequency, intensity, size, pattern, season, and severity) are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] Although the total area burned by wildfire is greatest in the western United States, the Southeast has the largest area burned by prescribed fire (see Case Study "Prescribed Fire") and the highest number of wildfires.[134,190] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6] Moreover, rapid urban expansion near managed forests has the potential to reduce opportunities to use prescribed fire, which could lead to native species declines, increased wildfire occurrence, and economic and health impacts.[134,191]

A recent example of the importance of fire lies in the forests of the southern Appalachians. Over the last century, invasive insects, logging, and pathogens have transformed forests in the region.[192] Warmer temperatures and insects have led to the loss of cold-adapted boreal communities, and flammable, fire-adapted tree species have been replaced by less flammable, fire-sensitive species—a process known as mesophication.[193,194] However, intense fires, like those observed in 2016, can halt the mesophication process. High temperatures, increases in accumulated plant material on the forest floor, and a four-month seasonal drought in the fall of 2016 collectively produced the worst wildfires the region has seen in a century. Intra-annual droughts, like the one in 2016, are expected to become more frequent in the future.[6] Thus, drought and greater fire activity[134] are expected to continue to transform forest ecosystems in the region (see Ch. 6: Forests, KM 1).

Case Study: Prescribed Fire

With wildfire projected to increase in the Southeast,[6,191] prescribed fire (the purposeful ignition of low-intensity fires in a controlled setting), remains the most effective tool for reducing wildfire risk.[4,195] Department of Defense (DoD) lands represent the largest reservoirs of biodiversity and native ecosystems in the region.[117] Military activities are a frequent source of wildfires, but increases in prescribed fire acres (Figure 19.19) show a corresponding decrease in wildfire ignitions for DoD.[4] Climate resilience by DoD is further achieved through restoration of native longleaf pine forests that occupy a wide range of site types, including wetland and well-drained soils—the latter leading many to characterize this forest as being drought resistant.[196,197,198,199] In addition to proactive adaptation through prescribed fire, DoD has been a leader in climate strategies that include regional conservation planning, ecosystem management, endangered species recovery, and research funding.

Wildlife and Prescribed Fire

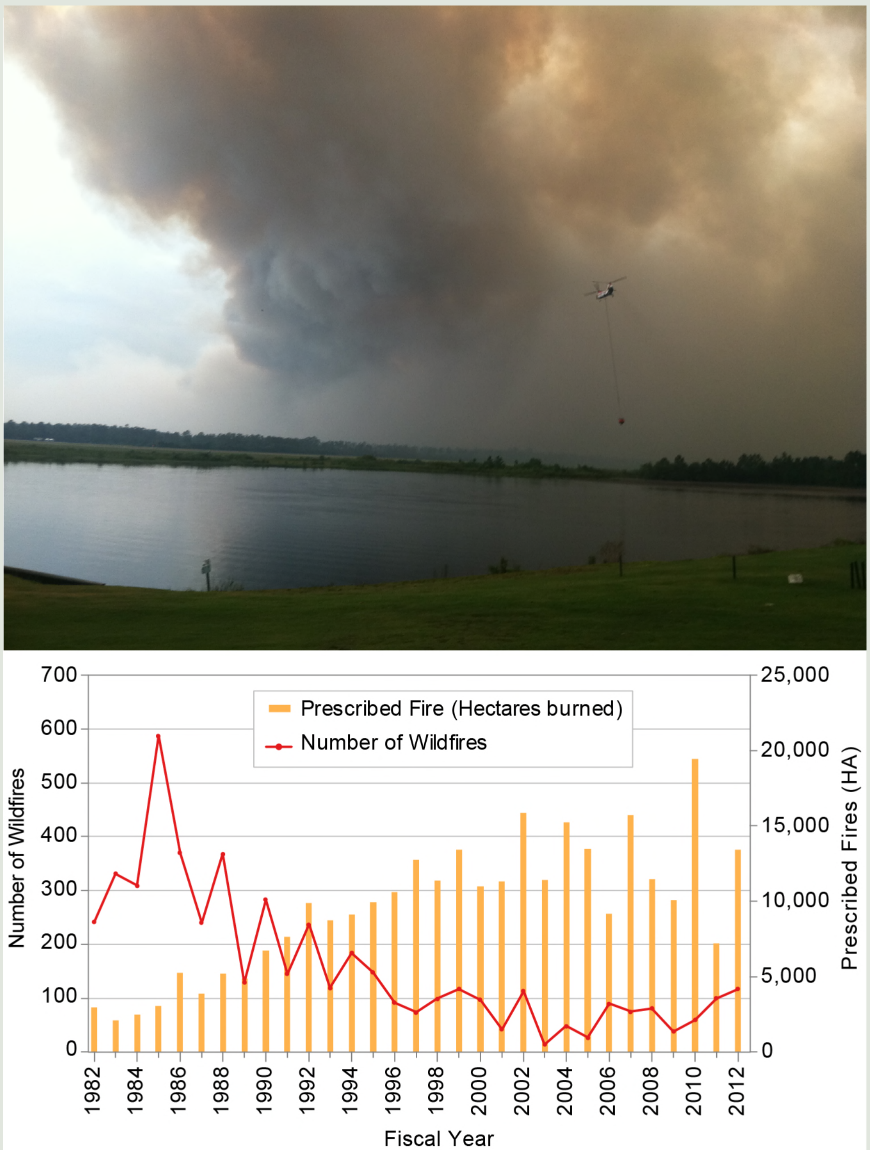


Figure 19.19: (top) A helicopter drops water on a 1,500-hectare wildfire on Hurlburt Field (Eglin Air Force Base) in Florida in June of 2012. (bottom) The increased use of prescribed fire at Ft. Benning, Georgia, led to a decrease in wildfire occurrence from 1982 to 2012. Photo credit: Kevin Hiers, Tall Timbers. Figure source: adapted from Addington et al. 2015.[4] Reprinted by permission of CSIRO Australia, ©CSIRO.

Rising Sea Levels and Hurricanes

Rising sea levels and potential changes in hurricane intensity are aspects of climate change that are expected to have a tremendous effect on coastal ecosystems in the Southeast (Ch. 8: Coastal, KM 2; Ch. 9: Oceans, KM 1). Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and salinity, sea level rise will result in the rapid conversion of these systems to tidal saline habitats. Historically, coastal ecosystems in the region have adjusted to sea level rise by vertical and horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and saltwater intrusion will allow salt-tolerant coastal ecosystems to move inland at the expense of upslope and upriver ecosystems.[128,202,203,204,205,206,207,208] Where barriers are present (for example, levees and other coastal infrastructure), the potential for landward migration of natural systems will be reduced and certain coastal habitats will be lost (Ch. 20: U.S. Caribbean, KM 3).[204] With higher sea levels and increasing saltwater intrusion, the high winds, high precipitation rates, storm surges, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

An example of the effects of rising sea levels can be found in Louisiana, which faces some of the highest land loss rates in the world. The ecosystems of the Mississippi River Delta provide at least $12–$47 billion (in 2017 dollars) in benefits to people each year.[155] These benefits include hurricane storm protection, water supply, furs, habitat, climate stability, and waste treatment. However, between 1932 and 2016, Louisiana lost 2,006 square miles of land area (see Case Study "A Lesson Learned for Community Resettlement"),[211] due in part to high rates of relative sea level rise.[212,213,214,215] The rate of wetland loss during this period equates to Louisiana losing an area the size of one football field every 34 to 100 minutes.[211] To protect and restore the Louisiana coast, the Louisiana Coastal Protection and Restoration Authority (CPRA) has worked with local, state, and federal partners to iteratively develop a 2017 Coastal Master Plan that identifies investments that can provide direct restoration and risk reduction benefits.[216] The aim of the 50-year, $50-billion strategy is to sustain Louisiana's coastal ecosystems, safeguard coastal populations, and protect vital economic and cultural resources.[216]

Drought and Extreme Rainfall

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events like drought and heavy rainfall. Drought and extreme heat can result in tree mortality and transform the region's forested ecosystems (Ch. 6: Forests, KM 1).[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems,[224] for example by contributing to mortality and ecological transformations in salt marshes,[225,226] mangrove forests,[227,228,229,230,231] and tidal freshwater forests.[232] In addition to drought, extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that results from extreme rainfall can also result in mortality, such as the dieback of critical foundation plant species, and other large impacts to natural systems.[233] In combination, future increases in the frequency and severity of both extreme drought and extreme rainfall are expected to transform many ecosystems in the Southeast region. Natural systems in the region will have to become resistant and resilient to both too little water and too much water. The ecological transformations induced by these extreme events will affect many of the benefits that natural systems provide to society.

Warming Ocean Temperatures

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems (Ch. 9: Oceans, KM 3).[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] Due to climate change, warming ocean temperatures in the coming decades are expected to transform many marine and coastal ecosystems across the Southeast. However, the impacts to coral reef ecosystems in the region have been and are expected to be particularly dire. Coral reefs are biologically diverse ecosystems that provide many societal benefits, including coastal protection from waves, habitat for fish, and recreational and tourism opportunities.[238,239] However, coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Small increases in ocean temperature can cause corals to expel the symbiotic algae upon which they depend for nourishment. When this happens, corals lose their color and die in a process known as coral bleaching (Ch. 9: Oceans, KM 1). Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast region will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249] When coral reefs are lost, coastal communities lose the many benefits provided by these valuable ecosystems, including lost tourism opportunities, a decline in fisheries, and a decrease in wave protection.[246,247]

Key Message 4

Economic and Health Risks for Rural Communities

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

In the Southeast, over 56% of land remains rural (nonmetropolitan) and home to approximately 16 million people, or about 17% percent of the region's population.[250] These rural areas are important to the social and economic well-being of the Southeast. Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate change. The Southeast has the second highest number of farmworkers hired per year compared to other National Climate Assessment (NCA) regions.[251] Climate trends and possible climate futures show patterns that are already impacting—and are expected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity (Ch. 10: Ag & Rural, KM 3). For example, shrimping, oystering, and fishing along the coast are long-standing traditions in the coastal economy that are expected to face substantial challenges. For example, by the end of the century, annual oyster harvests in the Southeast are projected to decline between 20% (19%–22%) under a lower scenario (RCP4.5) and 46% (44%–48%) under a higher scenario (RCP8.5), leading to projected price increases of 48% (RCP4.5) to 140% (RCP8.5).[35] Projected warming ocean temperatures, sea level rise, and ocean and coastal acidification are raising concern over future harvests (Ch. 9: Oceans, KM 2).[35,252] While adaptation and resilience can moderate climate change impacts, rural areas generally face other stressors, such as poverty and limited access to healthcare, which will make coping to these climate-related challenges more difficult.

Heat-related stresses are presently a major concern in the Southeast. Future temperature increases are projected to pose challenges for human health. While recent regional temperature trends have not shown the same consistent rate of daytime maximum temperature increase as observed in other parts of the United States, climate model simulations strongly suggest that daytime maximum temperatures are likely to increase as humans continue to emit greenhouse gases into the atmosphere.[13] The resulting temperature increases are expected to add to the heat health burden in rural, as well as urban, areas.[35] Projected temperature increases also pose challenges for crop production dependent on periods of lower temperatures to reach full productivity. Drought has been a recurrent issue in the Southeast affecting agriculture, forestry, and water resources.[253] With rapid growth in population and overall demand, drought is increasingly a concern for water resource management sectors such as cities, ecosystems, and energy production.

Diverse Rural Regions

Urban and rural areas exist along a continuum from major metro areas to suburbs, small towns, and lightly populated places. These areas are linked through many processes, commuting patterns, and shared central services, such as airports and hospitals, that connect the risks. Rapid population growth with associated urbanization and suburbanization over the last several decades has resulted in a more fine-grained forest landscape with smaller and more numerous forest patches.[254] Agriculture, manufacturing, tourism, and other major economic sectors are spread across the Southeast region. Rural counties in the region generally have a diversified economy with a relatively low percentage being heavily dependent on one sector. While well known for agriculture and forestry, rural areas also support manufacturing and tourism.[250]

In 2013, approximately 34% of the U.S. manufacturing output, or about $700 billion (dollar year not reported), came from the Southeast and Texas, including rural areas.[255] While manufacturing growth has been particularly strong in the Southeast in recent years, future climate changes would pose challenges for economic competitiveness. For companies involved in food processing, there are additional secondary economic risks associated with climate impacts on crops and livestock that could alter price or availability.[64,255] Facilities that are energy- or water-intensive are more likely to face increases in the costs and decreases in the availability of these resources, with potential impacts to their economic competitiveness.[246,255]

Energy production, and its dependence on water availability, is a key concern in the Southeast, given the region's growing population and large, diversified economy. An increasing number of high heat and dry days as the climate warms poses a risk to efficient power generation, particularly under conditions where the mode of primary generation moves towards natural gas and water-intensive nuclear power.[256]

Risks to Agriculture and Forestry

Agriculture, livestock rearing, and forestry activities are widespread and varied through the Southeast region.[7] Climate change is expected to have an overall negative impact on agricultural productivity in the United States,[35] although some crops could also become newly viable alternatives (Key Message 3, Figure 19.15). Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems (Ch. 10: Ag & Rural, KM 1).[7] In particular, precipitation trends for the Southeast region show an inclination towards slightly drier summers, which could reduce productivity, and wetter fall seasons, which can make it difficult to harvest the full crop. Multimodel averages of climate model simulations (CMIP3 [SRES A2] and CMIP5 [RCP8.5] higher scenarios) show that there is a greater risk of drier summers by the middle of the century in the western portion of the Southeast and in southern Florida, while wetter fall seasons are more likely in the eastern portion of the region.[257]

The conditions for raising and harvesting crops and livestock are projected to change. Higher temperatures can result in decreasing productivity of some cultivated crops, including cotton, corn, soybeans, and rice.[7] Livestock, which includes hogs and pigs, horses, ponies, mules, burros, and donkeys as well as poultry and processed poultry for consumption (for example, chicken nuggets), is a large component of the agricultural sector for these states and the Nation.[258] Livestock are all vulnerable to heat stress, and their care under projected future conditions would require new or enhanced adaptive strategies (Ch. 10: Ag & Rural, KM 3).

Recent changes in seasonal temperatures that are critical for plant development will continue to impact regionally important crops. Plants collected from the wild may become less available as the ideal conditions for their growth shift to other areas (see Case Study "Mountain Ramps"). Peaches—an important crop in the Southeast—require an adequate period of cool temperatures, called the chill period, to produce yields that are economically viable. Peaches also require warm temperatures at specific times during their development.[259] If the warm temperatures come too early, the chill periods could be too short or the peach blossoms can flower too soon and be in danger of late freeze impacts. A late freeze in March 2017 caused over a billion dollars of damages to peaches and other fruit crops.[84] To assist peach growers in adapting to such changes, researchers are working to develop peach varieties that can produce quality fruits in warmer winters and are developing winter chill models that can assist in adaptation planning efforts.[260,261]

Forests, both natural and plantation, in the Southeast are vulnerable to climate variability and change. Southeastern forests represent almost 27% of the U.S. total[262] and are the highest-valued crop in the region.[7] The vast majority of forest is held in private hands, primarily corporate. Forest cover ranges from almost 50% to 80% in these states, creating large areas of interface between populations and forests.[262] Jobs in timber, logging, and support for agriculture and forestry totaled approximately 458,000.[263] (See Ch. 6: Forests, KM 3 for additional discussion on forest change impacts on rural landscapes.)

The Southeast is one of the most dynamic regions for forest change on the globe,[269] though much of the change owes to intensive rotations of pine production and economic forces that drive frequent conversion between forest and agricultural uses in rural areas.[270,271] Climate is expected to have an impact on the region's forests primarily through changes in moisture regimes.[272] Species migration westward across the eastern United States in response to changing precipitation patterns has already been noted.[273] Drought is likely to alter fire regimes and further interact with species distributions (see Key Message 3). The interactions of altered precipitation and natural disturbances will be important in understanding impacts to the forests not dominated by industrial forestry (Ch. 6: Forests, KM 1 and KM 3).[274]

Wildfire is a well-known risk in the Southeast region, where it occurs with greater frequency than any other U.S. region.[275] However, mitigation strategies, particularly the use of prescribed fire, can significantly reduce wildfire risk and have been widely adopted across rural communities in the Southeast.[190] A doubling of prescribed fire at the landscape scale has been found to reduce wildfire ignitions by a factor of four,[4] while it is well documented that prescribed fire reduces the potential for crown fire in treated forest stands.[276] With greater projected fire risks,[191,277] more attention on how to foster fire-adapted communities offers opportunities for risk reduction (see Case Study "Prescribed Fire" and Key Message 3).[278,279]

Case Study: Mountain Ramps

The Cherokee have been harvesting ramps, a wild onion (*Allium tricoccum*), in the southern Appalachians, their ancestral homelands, for thousands of years.[264,265] Collecting ramps for food sustenance is only one aspect of this cultural tradition. The family-bound harvesting techniques are equally as important and make up part of the deeply held tribal lifeways (Ch. 15: Tribes, KM 2). Ramps emerge in springtime and provide important nutrients after a long winter with a dearth of fresh vegetables. These plants grow in moist forest understory areas that are sensitive to temperature and soil moisture.[266]

Figure 19.20: This up-close image of a ramp (*Allium tricoccum*), harvested from the wild, shows leaves and the bulb/corm of the plant. Photo credit: Gary Kaufman, USDA Forest Service Southern Research Station.

In the southern Appalachians, ramps are threatened by two major processes: overharvesting pressures and a changing climate that could expose these plants to higher temperatures and lower soil moisture conditions during sensitive growth periods (Ch. 10: Ag & Rural, KM 1).[267,268] Although ramps are found all along the Appalachian mountain range, on Cherokee ancestral lands, they are already in their southernmost range. Climate change thus acts to increase the vulnerability of this plant to the existing stressors.

Heat, Health, and Livelihoods

Heat-related health threats are already a risk in outdoor jobs and activities. While heat illness is more often associated with urban settings, rural populations are also at risk. For example, higher rates of heat-related illness have been reported in rural North Carolina compared to urban locations.[280] However, strategies to reduce health impacts on hot days, such as staying indoors or altering times outdoors, are already contributing to reducing heat-related illness in the Southeast.[281]

Workers in the agriculture, forestry, hunting, and fishing sectors together with construction and support, waste, and remediation services work are the most highly vulnerable to heat-related deaths in the United States, representing almost 68% of heat-related deaths nationally.[282] Six of the ten states with the highest occupational heat-related deaths in these sectors are in the Southeast region, accounting for 28.6% of occupational heat-related deaths between 2000 and 2010.[282] By 2090, under a higher scenario (RCP8.5), the Southeast is projected to have the largest heat-related impacts on labor productivity in the country, resulting in average annual losses of 570 million labor hours, or $47 billion (in 2015 dollars, undiscounted), a cost representing a third of total national projected losses, although these figures do not include adaptations by workers or industries (Figure 19.21).[35]

Investing in increased cooling is one likely form of adaptation. Among U.S. regions, the Southeast is projected to experience the highest costs associated with meeting increased electricity demands in a warmer world.[35]

Compounding Stresses and Constraints to Adaptation

The people of the rural Southeast confront a number of social stresses likely to add to the challenges posed by increases in climate stresses.[283] Rural communities tend to be more vulnerable due to factors such as demography, occupations, earnings, literacy, poverty incidence, and community capacities (Ch. 10: Ag & Rural, KM 4).[8,9,10] Reducing stress associated with these factors can increase household and community resilience.[9,284]

Projected Changes in Hours Worked

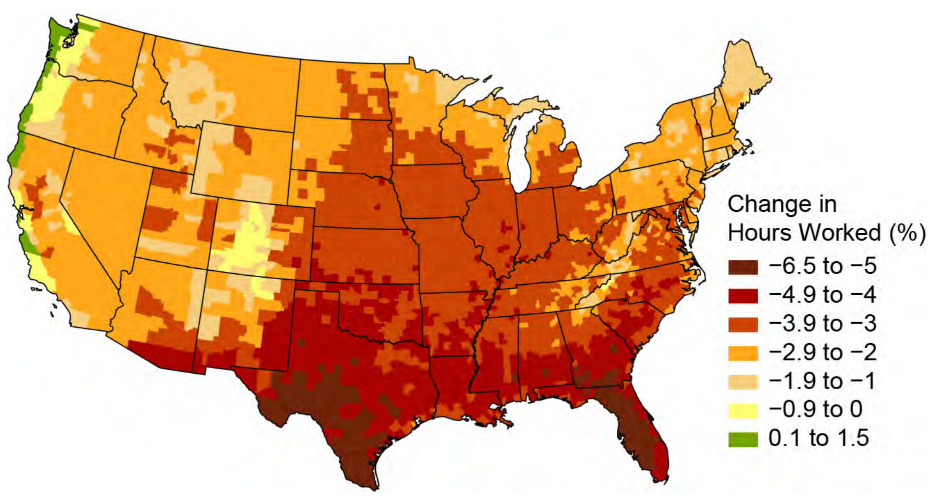


Figure 19.21: This map shows the estimated percent change in hours worked in 2090 under a higher scenario (RCP8.5). Projections indicate an annual average of 570 million labor hours lost per year in the Southeast by 2090 (with models ranging from 340 million to 820 million labor hours).[35] Estimates represent a change in hours worked as compared to a 2003–2007 average baseline for high-risk industries only. These industries are defined as agriculture, forestry, and fishing; hunting, mining, and construction; manufacturing, transportation, and utilities. Source: adapted from EPA 2017.[35]

Persistent rural poverty stands out in the Southeast (Figure 19.22). The rural counties in the region are experiencing higher levels of population loss (13% of rural counties lost population) and low educational attainment (38% of rural counties), with 35% of rural counties experiencing poverty rates of more than 20% persisting over approximately 30 years.[10] The Southeast is expected to experience the highest costs associated with meeting increased energy demands; an estimated $3.3 billion each year under a higher scenario (RCP8.5) and $1.2 billion annually under a lower scenario (RCP4.5) by the end of the century.[35] Energy poverty is a situation "where individuals or households are not able to adequately heat or provide other required energy services in their homes at affordable cost."[285] A case study from rural eastern North Carolina further explains energy poverty as a function of the energy efficiency of the home, energy provision infrastructure, physical health, low incomes, and support of social networks, which collectively influence households' choices about the amount of heating and cooling they can afford.[286] The National Weather Service (NWS) calculates degree days,[287] a way of tracking energy use. NWS starts with the assumption that when the average outside temperature is 65°F, heating or cooling is not needed in order to be comfortable. The difference between the average daily temperature and 65°F is the number of cooling or heating degrees for that day. These days can be added up over time—a month or a year—to give a combined estimate of energy needed for heating or cooling. Although heating costs are expected to decrease as the climate warms in the Southeast, the number of cooling degree days is expected to increase and the length of the cooling season expected to expand, increasing energy demand and exacerbating rural energy poverty (Figure 19.22).

The ability to cope with current and potential impacts, such as flooding, is further reduced by limited county resources. A study of hazard management plans (2004–2008) in 84 selected rural southeastern counties found these plans scored low across various criteria.[288] The rural, geographically remote locations contributed to more difficult logistics in reaching people. Interviewees also identified low-income and minority communities, substandard housing, lack of access to vehicles for evacuation, limited modes of communication, and limited local government capacity as contributing factors to difficulties in emergency planning.[288]

The healthcare system in the Southeast is already overburdened and may be further stressed by climate change. Between 2010 and 2016, more rural hospitals closed in the Southeast than any other region, with Alabama, Georgia, Mississippi, and Tennessee being among the top five states for hospital closures.[289] This strain, when combined with negative health impacts from climate change stressors (such as additional patient demand due to extreme heat and vector-borne diseases and greater flood risk from extreme precipitation events), increases the potential for disruptions of health services in the future. The Green River District Health Department recently did an assessment of ways to reduce vulnerability to negative health impacts of climate change in a mostly rural region of western Kentucky.[290] As a result, the local health department plans to enhance existing epidemiology, public health preparedness, and community health assessment services.[290]

Projected Changes in Cooling Degree Days

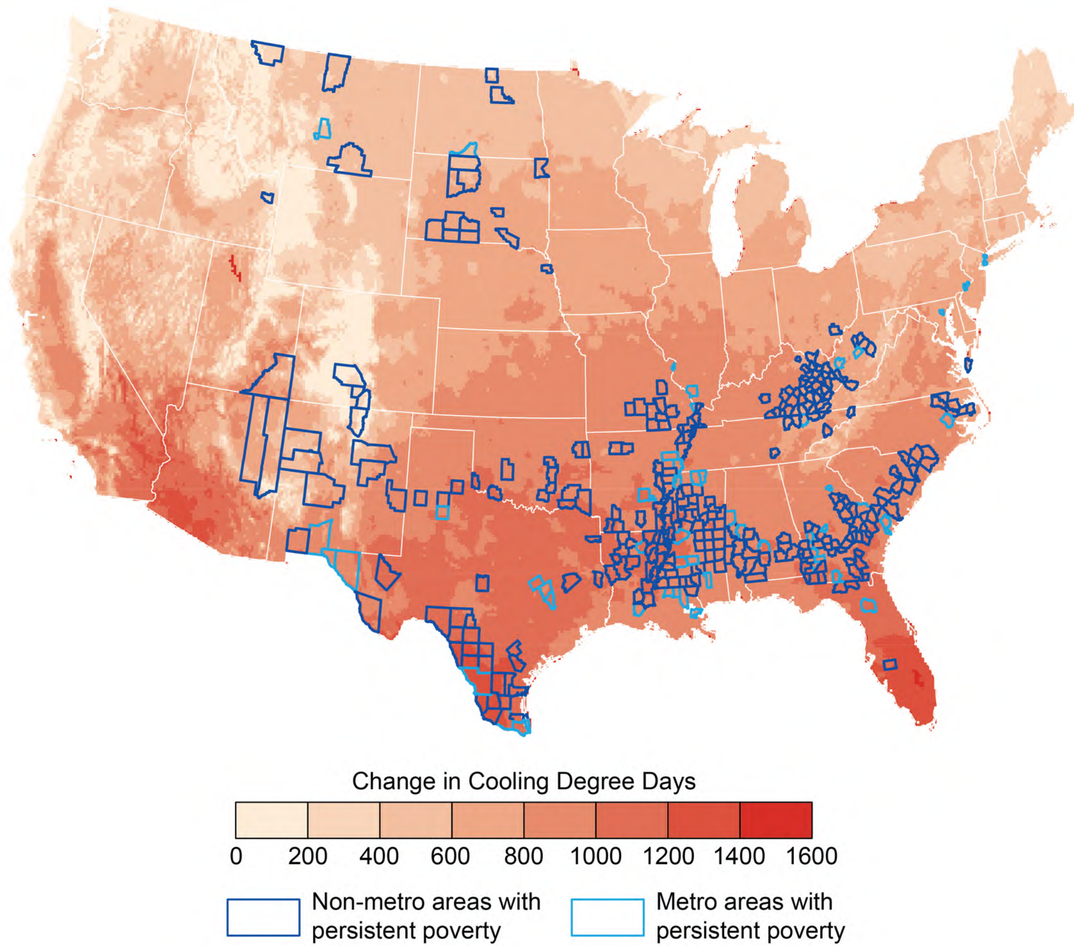


Figure 19.22: The map shows projected changes in cooling degree days by the mid-21st century (2036–2065) under the higher scenario (RCP8.5) based on model simulations. Rural counties experiencing persistent poverty are concentrated in the Southeast, where the need for additional cooling is expected to increase at higher rates than other areas of the country by mid-century. Sources: NOAA NCEI, CICS-NC, and ERT, Inc.

Acknowledgments

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Opening Image Credit

Red mangrove: © Katja Schulz/Flickr (CC BY 2.0). Adaptation: cropped top and bottom to conform to the size needed for publication.

Traceable Accounts

Process Description

Prior to identifying critical issues for the Southeast assessment focuses for the Fourth National Climate Assessment (NCA4), the Chapter Lead (CL) contacted numerous professional colleagues representing various geographic areas (e.g., Florida, Louisiana, and South Carolina) for expert opinions on critical climate change related issues impacting the region, with a particular emphasis on emerging issues since the Third National Climate Assessment (NCA3) effort.[77] Following those interviews, the CL concluded that the most pressing climate change issues to focus on for the NCA4 effort were extreme events, flooding (both from rainfall and sea level rise), wildfire, health issues, ecosystems, and adaptation actions. Authors with specific expertise in each of these areas were sought, and a draft outline built around these issues was developed. Further refinement of these focal areas occurred in conjunction with the public Regional Engagement Workshop, held on the campus of North Carolina State University in March 2017 and in six satellite locations across the Southeast region. The participants agreed that the identified issues were important and suggested the inclusion of several other topics, including impacts on coastal and rural areas and people, forests, and agriculture. Based on the subsequent authors' meeting and input from NCA staff, the chapter outline and Key Messages were updated to reflect a risk-based framing in the context of a new set of Key Messages. The depth of discussion for any particular topic and Key Message is dependent on the availability of supporting literature and chapter length limitations.

Key Message 1

Urban Infrastructure and Health Risks

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

Description of evidence base

Multiple studies have projected that urban areas, including those in the Southeast, will be adversely affected by climate change in a variety of ways. This includes impacts on infrastructure[41,42,43,291,292,293] and human health.[30,31,38,294] Increases in climate-related impacts have already been observed in some Southeast metropolitan areas (e.g., Habeeb et al. 2015, Tzung-May Fu et al. 2015[12,39]).

Southeastern cities may be more vulnerable than cities in other regions of the United States due to the climate being more conducive to some vector-borne diseases, the presence of multiple large coastal cities at low elevation that are vulnerable to flooding and storms, and a rapidly growing urban and coastal population.[22,295,296]

Many city and county governments, utilities, and other government and service organizations have already begun to plan and prepare for the impacts of climate change (e.g., Gregg et al. 2017; FTA 2013; City of Fayetteville 2017; City of Charleston 2015; City of New Orleans 2015; Tampa Bay Water 2014; EPA 2015; City of Atlanta 2015, 2017; Southeast Florida Regional Climate Change Compact 2017[44,45,46,50,91,246,297,298,299]). A wide variety of adaptation options are available, offering opportunities to improve the climate resilience, quality of life, and economy of urban areas.[77,300,301,302,303,304]

Major uncertainties

Population projections are inherently uncertain over long time periods, and shifts in immigration or migration rates and shifting demographics will influence urban vulnerabilities to climate change. The precise impacts on cities are difficult to project. The scope and scale of adaptation efforts, which are already underway, will affect future vulnerability and risk. Technological developments (such as a potential shift in transportation modes) will also affect the scope and location of risk within cities. Newly emerging pathogens could increase risk of disease in the future, while successful adaptations could reduce public health risk.

Description of confidence and likelihood

There is *very high confidence* that southeastern cities will *likely* be impacted by climate change, especially in the areas of infrastructure and human health.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

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

Description of evidence base

Multiple lines of research have shown that global sea levels have increased in the past and are projected to continue to accelerate in the future due to increased global temperature and that higher local sea level rise rates in the Mid-Atlantic and Gulf Coasts have occurred.[51,52,53,54,55,56,57,59,61,62]

Annual occurrences of high tide flooding have increased, causing several Southeast coastal cities to experience all-time records of occurrences that are posing daily risks.[1,52,58,60,61,63,67,68]

There is scientific consensus that sea level rise will continue to cause increases in high tide flooding in the Southeast as well as impact the frequency and duration of extreme water level events, causing an increase in the vulnerability of coastal populations and property.[1,60,63,67,68]

In the future, coastal flooding is projected to become more serious, disruptive, and costly as the frequency, depth, and inland extent grow with time.[1,2,35,64,65,67,68]

Many analyses have determined that extreme rainfall events have increased in the Southeast, and under higher scenarios, the frequency and intensity of these events are projected to increase.[19,21,88]

Rainfall records have shown that since NCA3, many intense rainfall events (approaching 500-year events) have occurred in the Southeast, with some causing billions of dollars in damage and many deaths.[68,82,84]

The flood events in Baton Rouge, Louisiana, in 2016 and in South Carolina in 2015 provide real examples of how vulnerable inland and coastal communities are to extreme rainfall events.[81,85,86]

The socioeconomic impacts of climate change on the Southeast is a developing research field.[65,71]

Major uncertainties

The amount of confidence associated with the historical rate of global sea level rise is impacted by the sparsity of tide gauge records and historical proxies as well as different statistical approaches for estimating sea level change. The amount of unpredictability in future projected rates of sea level rise is likely caused by a range of future climate scenarios projections and rate of ice sheet mass changes. Flooding events are highly variable in both space and time. Detection and attribution of flood events are difficult due to multiple variables that cause flooding.

Description of confidence and likelihood

There is *high confidence* that flood risks will *very likely* increase in coastal and low-lying regions of the Southeast due to rising sea level and an increase in extreme rainfall events. There is *high confidence* that Southeast coastal cities are already experiencing record numbers of high tide flooding events, and without significant adaptation measures, it is *likely* they will be impacted by daily high tide flooding.

Key Message 3

Natural Ecosystems Will Be Transformed

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

Description of evidence base

Winter temperature extremes, fire regimes, sea levels, hurricanes, rainfall extremes, drought extremes, and warming ocean temperatures greatly influence the distribution, abundance, and performance of species and ecosystems.

Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[30,48,127,132,135,138,139,140,141,142,143,144,145,148,149,150,152,166,167,168,169,170,172,173,174,175,176,177,178] In the future, warmer winter temperatures are expected to facilitate the northward movement of cold-sensitive species, often at the expense of cold-tolerant species.[132,135,142,145,149,150,152,166,169,173,179] Certain ecosystems are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (i.e., ecological regime shifts).[135,145,152]

Changing fire regimes are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6]

Hurricanes and rising sea levels are aspects of climate change that will have a tremendous effect on coastal ecosystems in the Southeast. Historically, coastal ecosystems in the region have adjusted to sea level rise via vertical and/or horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and some coastal ecosystems will move inland at the expense of upslope and upriver ecosystems.[203,204] Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and/or salinity, sea level rise will result in the comparatively rapid conversion of these systems to tidal saline habitats. In addition to sea level rise, climate change is expected to increase the impacts of hurricanes; the high winds, storm surges, inundation, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events. Extreme drought events are expected to become more frequent and severe. Drought and extreme heat can result in tree mortality and transform southeastern forested ecosystems.[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems.[224,225,226,227,228,229,232] Extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that result from extreme rainfall events can also result in mortality and large impacts to natural systems.[233] In combination, future increases in both extreme drought and extreme rainfall are expected to transform many southeastern ecosystems.

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems.[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] The impacts to coral reef ecosystems have been and are expected to be particularly dire. Coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249]

Major uncertainties

In the Southeast, winter temperature extremes, fire regimes, sea level fluctuations, hurricanes, extreme rainfall, and extreme drought all play critical roles and greatly influence the distribution, structure, and function of species and ecosystems. Changing climatic conditions (particularly, changes in the frequency and severity of climate extremes) are, however, difficult to replicate via experimental manipulations; hence, ecological responses to future climate regimes have not been fully quantified for all species and ecosystems. Natural ecosystems are complex and governed by many interacting biotic and abiotic processes. Although it is possible to make general predictions of climate change effects, specific future ecological transformations can be difficult to predict, especially given the number of interacting and changing biotic and abiotic factors in any specific location. Uncertainties in the range of potential future changes in multiple and concurrent facets of climate and land-use change also affect our ability to predict changes to natural systems.

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., changing winter temperatures extremes, changing fire regimes, rising sea levels and hurricanes, warming ocean temperatures, and more extreme rainfall and drought) will *very likely* affect natural systems in the Southeast region. These climatic drivers play critical roles and greatly influence the distribution, structure, and functioning of ecosystems; hence, changes in these climatic drivers will transform ecosystems in the region and greatly alter the distribution and abundance of species.

Key Message 4

Economic and Health Risks for Rural Communities

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

Description of evidence base

Analysis of the sensitivity of some manufacturing sectors to climate changes anticipates secondary risks associated with crop and livestock productivity.[64,255]

Multiple analyses anticipate that energy- or water-intensive industries could face water stress and increased energy costs.[8,64,255,256]

A large body of evidence addresses the sensitivity of many crops grown in the Southeast to changing climate conditions including increased temperatures, decreased summer rainfall, drought, and change in the timing and duration of chill periods.[7,35] Extensive research documents livestock sensitivity to heat stress.[7]

Multiple lines of evidence indicate that forests are likely to be impacted by changing climate, particularly moisture regimes and potential changes in wildfire activity.[191,195,272,274] There is extensive research on heat-related illness and mortality among those living and working in the Southeast. While there is more evidence focused on urban areas, limited research has identified higher levels of heat-related illness in rural areas.[280,281] Research on occupational heat-related mortality identifies some of the Nation's highest levels in southeastern states.[282] Computer model simulations of heat-related reductions in labor productivity anticipate the greatest losses will occur in the Southeast. However, these models do not account for adaptations that may reduce estimated losses.[35,64] By the end of the century, mean annual electricity costs are estimated at $3.3 billion each year under RCP8.5 (model range: $2.4 to $4.2 billion; in 2015 dollars, undiscounted) and mean $1.2 billion each year under RCP4.5 (model range $0.9 to $1.9 billion; in 2015 dollars, undiscounted).[35]

Rural communities tend to be vulnerable due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10,250,283,284,305] Reducing the stress created by such factors can improve resilience.[9,284] The availability and accessibility of planning and health services to support coping with climate-related stresses are limited in the rural Southeast.[288,289]

Major uncertainties

There are limited studies documenting direct connections between climate changes and economic impacts. Models are limited in their ability to incorporate adaptation that may reduce losses. These factors restrict the potential to strongly associate declines in agricultural and forest productivity with the level of potential economic impact.

Projections of potential change in the frequency and extent of wildfires depend in part on models of future population growth and human behavior, which are limited, adding to the uncertainty associated with climate and forest modeling.

Many indicators of vulnerability are dynamic, so that adaptation and other changes can affect the patterns of vulnerability to heat and other climate stressors over time. Limited studies indicate concerns over the planning and preparedness of capacity at local levels; however, information is limited.

Projected labor hours lost vary by global climate model, time frame, and scenario, with a mean of 0.57 and a model range of 0.34–0.82 billion labor hours lost each year for RCP8.5 by 2090. The annual mean projected losses are roughly halved (0.28 billion labor hours) and with a model range from 0.19 to 0.43 billion labor hours lost under RCP4.5 by 2090.[35]

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., rising temperatures, changing fire regimes, rising sea levels, and more extreme rainfall and drought) will *very likely* affect agricultural and forest products industries, potentially resulting in economic impacts. There is *high confidence* that increases in temperature are *very likely* to increase heat-related illness, deaths, and loss of labor productivity without greater adaptation efforts.

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Exhibit 2

Billion-Dollar Weather and Climate Disasters: Events

Below is a table of U.S. billion-dollar disaster events including summaries, report links, and statistics.

State: United States Begin Year: 1980 End Year: 2021

All Disasters Drought Flooding Freeze Severe Storm Tropical Cyclone Wildfire Winter Storm

<< < > >> CPI-Adjusted Unadjusted

Between 1980 and 2021, 19 Winter Storm, 18 Wildfire, 28 Drought, 52 Tropical Cyclone, 132 Severe Storm, 33 Flooding, and 9 Freeze billion-dollar disaster events affected the United States (CPI-adjusted).

Download:

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
Northwest, Central, Eastern Winter Storm and Cold Wave † *February 2021*	2021-02-10	2021-02-19	Historic cold wave and winter storm impacts many northwest, central and eastern states. Temperature departures exceeding 40.0 degrees F (22.2 degrees C) below normal occurred from Nebraska southward to Texas. The prolonged arctic air caused widespread power outages in Texas, as well as other southern states, with multiple days of sustained below-freezing temperatures. At the peak of the outage, nearly 10 million people were without power. Additional impacts were frozen water pipes, which burst upon thawing causing water damage to buildings. These extreme conditions also caused or contributed to the deaths of more than 125 people in Texas alone, and this number is expected to increase further, after additional reporting. There were also snow and ice impacts across numerous states including Oklahoma, Arkansas, Missouri, Illinois, Kentucky, Tennessee, Louisiana, Mississippi, Colorado, Oregon and Washington. Damage costs are not yet certain for this events but already exceed $10.0 billion making it the most costly U.S. winter storm/coldwave on record surpassing the March 1993 'Storm of the Century'.	TBD	138
Western Wildfires - California, Oregon, Washington Firestorms † *Fall 2020*	2020-08-01	2020-12-30	A record-breaking U.S. wildfire season burned more than 10.2 million acres. California more than doubled its previous annual record for area burned (last set in 2018) with over 4.1 million acres. Five of the top six largest wildfires on record in California (dating to 1932) burned during August and September. The August Complex was the largest California wildfire, which began as 37 separate wildfires within the Mendocino National Forest, set off after storms caused >10,000 lightning strikes across Northern California. Approximately 10,500 structures were damaged or destroyed across California. Oregon also had historic levels of wildfire damage, as over 2,000 structures burned. These wildfires spread rapidly and destroyed several small towns in California, Oregon and Washington. Colorado also had a severe wildfire season, as its three largest wildfires on record burned during 2020. Dense wildfire smoke also produced hazardous air quality that affected millions of people that also included major cities for weeks. Hundreds of additional wildfires also burned across other Western states.	$16.6 CI	46
Western/ Central Drought and Heatwave † *Summer-Fall 2020*	2020-06-01	2020-12-30	Widespread, continuous drought and record heat affected more than a dozen Western and Central states for much of the summer, fall and into the winter months. Persistent above-average temperatures and precipitation deficits caused D3 (extreme) and D4 (exceptional) drought coverage in December that was the largest extent since August 2012. Death Valley recorded a temperature of 130 degrees F - the highest measured temperature globally in decades - while Los Angeles county recorded a record high of 121 degrees F. There were considerable crop and livestock impacts across the West and Central states from both the persistent heat and increasingly dry conditions. The combined drought and heat also assisted in drying out vegetation across the West that contributed to the Western wildfire potential and severity.	$4.5 CI	45

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
Tropical Storm Eta † *November 2020*	2020-11-08	2020-11-12	Tropical Storm Eta made landfall in the Florida Keys on November 8 followed by a second landfall near Cedar Key on the west coast of Florida on November 10. Eta produced wind and heavy rain impacts in southern Florida. These impacts continued well inland, as Eta's energy merged with a cold front across several eastern states. This combination produced extreme rainfall across North Carolina and Virginia, which led to significant flooding that damaged homes, businesses and infrastructure. This flooding also caused one dozen fatalities.	$1.5 CI	12
Hurricane Zeta † *October 2020*	2020-10-28	2020-10-29	Hurricane Zeta was a category 2 hurricane that made landfall at Cocodrie, Louisiana with maximum sustained winds of 110 mph on October 28th. Zeta's path inland saw an acceleration of its quick landfall speed to nearly 40 mph, which allowed the wind fields to maintain some strength. These wind impacts propagated well inland affecting parts of Louisiana, Alabama, Mississippi, northern Georgia and into the Carolinas. Hurricane Zeta was the fifth tropical cyclone to make landfall in Louisiana during 2020 as part of a historically active Atlantic hurricane season.	$4.4 CI	6
Hurricane Delta † *October 2020*	2020-10-09	2020-10-11	Hurricane Delta was a category 2 hurricane that made landfall near Creole, Louisiana with winds of 100 mph on October 9. This was nearly the same location in which category 4 Hurricane Laura made landfall 6 weeks prior. Heavy rainfall, high winds, storm surge, and nearly one dozen EF-0 or EF-1 tornadoes caused damage across several states including Louisiana, eastern Texas, Mississippi and Georgia.	$2.9 CI	5
Hurricane Sally † *September 2020*	2020-09-15	2020-09-17	Hurricane Sally was a category 2 hurricane at landfall in Gulf Shores, Alabama. Wind gusts up to 100 mph and 20-30 inches of rainfall caused considerable flood and wind damage across Alabama, the Florida panhandle and into Georgia. Many homes and businesses in downtown Pensacola, FL were impacted from flooding produced by storm surge and heavy rainfall. 2020 is now the fourth consecutive year (2017-2020) that the U.S. has been impacted by a slow moving tropical cyclone that produced extreme rainfall and damaging floods - Harvey, Florence, Imelda and Sally.	$7.3 CI	5
Hurricane Laura † *August 2020*	2020-08-27	2020-08-28	Hurricane Laura was a powerful category 4 that made landfall at Cameron Parish, in southwestern Louisiana on August 27. Winds up to 150 mph and storm surge in excess of 15 feet caused heavy damage along the coast and inland to the city of Lake Charles. Many broken water systems and a severely damaged electrical grid in southern Louisiana will slow the recovery process. Laura was the strongest hurricane (by maximum sustained windspeed at landfall) to hit Louisiana since the 1856 Last Island hurricane. Laura also had highest landfall wind speed to impact the U.S. since Hurricane Michael in 2018. There were additional impacts to surrounding states including Texas, Mississippi and Arkansas.	$19.2 CI	42
Central Severe Weather - Derecho † *August 2020*	2020-08-10	2020-08-10	A powerful derecho traveled from southeast South Dakota to Ohio, a path of 770 miles in 14 hours producing widespread winds greater than 100 mph. The states most affected included Iowa, Illinois, Minnesota, Indiana and Ohio. This derecho caused widespread damage to millions of acres of corn and soybean crops across central Iowa. There was also severe damage to homes, businesses and vehicles particularly in Cedar Rapids, Iowa. In addition, there were 15 tornadoes across northeastern Illinois several affecting the Chicago metropolitan area. This is the third severe weather event (since 1980) with inflation-adjusted costs over $10.0 ($10.2) billion joining the late-April and May 2011 tornado outbreaks across the Southeastern and Central states, respectively.	$11.2 CI	4
Hurricane Isaias † *August 2020*	2020-08-03	2020-08-04	Hurricane Isaias made landfall in southeastern North Carolina as a category 1 storm. Isaias accelerated up the East Coast, resulting in widespread damage and power outages across New York, New Jersey and Pennsylvania. There was also considerable inland flooding most notably in Pennsylvania. In addition, 34 tornadoes developed across North Carolina, Virginia, Maryland, Delaware and New Jersey due to Isaias. Many tornadoes were weaker (EF-0 and EF-1) producing scattered damage to agriculture, structures and residences. Isaias also produced several EF-2 tornadoes and one EF-3 tornado that caused damage in coastal North Carolina and Virginia.	$4.8 CI	16
Hurricane Hanna † *July 2020*	2020-07-25	2020-07-26	Category 1 Hurricane Hanna made landfall at Padre Island, Texas on July 25 with sustained winds of 90 miles per hour. The impacts from wind, wave action and flooding were most notable in damaging coastal infrastructure and to the agriculture sector. The crop damage was most focused across the Rio Grande Valley in southern Texas.	$1.1 CI	0
Central Severe Weather † *July 2020*	2020-07-10	2020-07-11	Central severe weather producing hundreds of severe hail and high wind reports across numerous states including Nebraska, South Dakota, Minnesota, Kansas, Oklahoma, Iowa, Illinois and Indiana. These storms caused impacts to many homes, vehicles and businesses.	$1.2 CI	0

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
South Texas Hail Storms † *May 2020*	2020-05-27	2020-05-27	South Texas hail storms cause widespread impact to several cities with golf-ball sized hail damaging many homes, vehicles and businesses. The highest concentration of hail damage occurred across the northern portion of the San Antonio metroplex. There was also significant damage east of San Marcos, southeast of Waco and to the west and south of Bryan and College Station.	$1.4 CI	0
South, Central and Eastern Severe Weather † *May 2020*	2020-05-20	2020-05-23	A combination of thunderstorm high winds, hail and tornadoes affected numerous Southern, Central and Eastern states. The states most affected included Texas, Illinois and North Carolina with damage to homes, businesses and vehicles. Oklahoma, Arkansas, Indiana, Tennessee, Alabama, Georgia, Florida and South Carolina.	$1.6 CI	2
Central and Eastern Severe Weather † *May 2020*	2020-05-03	2020-05-05	Severe weather across several Central and Eastern states including Kansas, Missouri, Arkansas, Tennessee and South Carolina. High wind and hail damage was notably clustered across southern Missouri and western to central Tennessee, which were the states with the highest damage totals for the event.	$2.2 CI	2
Central, Southern and Eastern Severe Weather † *April 2020*	2020-04-27	2020-04-30	Severe weather across many Central, Southern and Eastern states produced primarily large hail and high winds that caused widespread damage to many homes, vehicles and businesses. The states affected included Oklahoma, Texas, Missouri, Arkansas, Louisiana, Virginia, Pennsylvania, Maryland, Delaware and New Jersey.	$1.1 CI	1
Southern Severe Weather † *April 2020*	2020-04-21	2020-04-23	Severe weather caused damage across many Southern states. The states most affected from a combination of high winds, hail and tornadoes included Texas, Oklahoma, Louisiana, Mississippi, Alabama, Georgia, Florida and Virginia. The states with the highest damage totals for the event were Oklahoma, Louisiana and Texas.	$1.4 CI	3
Southeast and Eastern Tornado Outbreak † *April 2020*	2020-04-12	2020-04-13	Outbreak of at least 140 tornadoes from Texas to Maryland including 3 EF4s, 12 EF3s, 20 EF2s, 77 EF1s and 28 EF0s. Damage was extensive and highly destructive to many homes, vehicles and businesses across more than a dozen Southeast and Eastern states.	$3.5 CI	35
North Central and Ohio Valley Hail Storms and Severe Weather † *April 2020*	2020-04-07	2020-04-08	Numerous hail storms caused widespread damage across many North Central and Ohio Valley states including Illinois, Iowa, Indiana, Ohio, Michigan, Wisconsin and Missouri. More than 20 tornadoes were also reorted across southern Indiana and Ohio. There was additional widespread high wind damage to homes, vehicles and businesses in many other surrounding states.	$3.0 CI	0
Midwest and Ohio Valley Severe Weather † *March 2020*	2020-03-27	2020-03-28	Severe weather caused damage across many Midwest and Ohio Valley states including Missouri, Oklahoma, Texas, Illinois, Indiana, Ohio, Arkansas, Kentucky, Tennessee, West Virginia and Pennsylvania. The states most affected from a combination of high winds and hail were Missouri, Ohio and Arkansas. There were also two dozen tornadoes across Iowa, Illinois, Indiana and Arkansas causing additional damage.	$2.6 CI	0
Tennessee Tornadoes and Southeast Severe Weather † *March 2020*	2020-03-02	2020-03-04	Powerful EF-3 and EF-4 tornadoes cause considerable damage across the Nashville metroplex and several counties east of Nashville. This damage included many homes, businesses, vehicles, 90 planes and numerous buildings at the Nashville airport. There was also additional hail and wind damage in the surrounding states including Alabama, Kentucky, Mississippi and Missouri.	$2.4 CI	25
South, East and Northeast Severe Weather † *February 2020*	2020-02-05	2020-02-07	Severe weather across many South, East and Northeastern states including AL, FL, GA, SC, LA, MS, TN, NC, VA, PA, RI, NY, NJ, MD and MA. There were more than 20 tornadoes clustered across central Mississippi into Tennessee. There were also hundreds of high wind damage reports from Florida to New Jersey, with the Carolinas and Florida receiving the most costly damage.	$1.3 CI	3

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
Southeast Tornadoes and Northern Storms and Flooding † *January 2020*	2020-01-10	2020-01-12	More than 80 tornadoes and severe storms caused damage across many southeastern states (AL, AR, GA, IL, IN, KY, LA, MS, MO, NC, OH, SC, TN, TX, VA, WI). Storms and severe flooding also impacted northern states including Michigan, Wisconsin and New York. Significant damage occurred along the shoreline of Lake Michigan to roads, the foundation of homes and to Port Milwaukee. These powerful waves were generated by high winds and a lack of seasonal ice cover.	$1.2 CI	10
California and Alaska Wildfires † *Summer-Fall 2019*	2019-06-01	2019-11-30	California experienced a damaging wildfire season in 2019, largely resulting from the Kincade and Saddle Ridge wildfires. In addition, a key California electrical utility provider turned off power to millions of homes and businesses several times during days with forecasted high winds and extremely dry conditions. This step was designed to minimize wildfires, with some success, but it also caused billions of dollars in losses to those affected. Alaska also suffered a near-historic wildfire season with more than 2.5 million acres burned. These wildfire conditions were primed due to Alaska's record-breaking heat and dry conditions during the summer months. July 2019 was the warmest month ever recorded in Alaska.	$4.6 CI	3
Texas Tornadoes and Central Severe Weather † *October 2019*	2019-10-20	2019-10-20	Numerous tornadoes caused widespread damage across northern Dallas damaging thousands of homes, vehicles, businesses and other public infrastructure. Tornadoes up to EF-3 intensity with maximum winds of 140 mph tracked across a large section of highly developed northern Dallas. Additionally high winds and hail damage also caused damage in other states including Oklahoma, Missouri, Arkansas, Louisiana and Tennessee.	$1.8 CI	2
Tropical Storm Imelda † *September 2019*	2019-09-17	2019-09-21	Tropical storm and its remnants cause 24 to 36 inches of rainfall over a 3-day period across a large area between Houston and Beaumont, Texas. The largest storm total, 43.39 inches, was reported at North Fork Taylors Bayou, Texas. Many thousands of homes, cars and businesses were impacted by flood water due to this extraordinarily heavy rainfall. Imelda is yet another of the historically extreme rainfall and flood events that have become a regular occurrence across Southeast Texas over the last 5 years.	$5.1 CI	5
Hurricane Dorian † *September 2019*	2019-08-28	2019-09-06	Category 1 hurricane makes landfall on the Outer Banks of North Carolina, after devastating the northern Bahama Islands as a historically-powerful and slow-moving hurricane. Dorian tracked offshore parallel to the Florida, Georgia and South Carolina coastline before making a North Carolina landfall, bringing a destructive sound-side surge that inundated many coastal properties and isolated residents who did not evacuate. Significant flood, severe storm, and tornado damage to many homes and businesses occurred on the Outer Banks of North Carolina. Dorian's intensification to a category 5 storm marks the fourth consecutive year, in which a maximum category 5 storm developed in the Atlantic basin - a new record. Dorian also tied the record for maximum sustained wind speed for a landfalling hurricane (185 mph) in the Atlantic, a record shared with the historic 1935 Labor Day Hurricane.	$1.7 CI	10
Mississippi River, Midwest and Southern Flooding † *July 2019*	2019-03-15	2019-07-31	Additional major flooding impacted many Southern Plains states significantly affecting agriculture, roads, bridges, levees, dams and other assets across many cities and towns. The states most affected were Oklahoma, Nebraska, Missouri, Illinois, Kansas, Arkansas, Kentucky, Tennessee, Texas, Mississippi and Louisiana. Very high water levels also disrupted barge traffic along the Mississippi River, which negatively impacted a variety of dependent industries. Indiana and Ohio were also affected by persistent heavy rainfall that flooded farmland, which prevented and reduced crop planting by millions of acres.	$6.4 CI	4
Colorado Hail Storms † *July 2019*	2019-07-04	2019-07-05	Colorado hail storms across the Denver and Fort Collins that damaged many homes and vehicles.	$1.0 CI	0
Arkansas River Flooding † *June 2019*	2019-05-20	2019-06-14	Historic flooding impacts the Arkansas River Basin with damage to homes, agriculture, roads, bridges and levees focused across eastern Oklahoma and western Arkansas. Thousands of homes, cars and businesses were flooded due a combination of high rivers, levee failure and persistently heavy rainfall from May 20 through June.	$3.1 CI	5
Rockies, Central and Northeast Tornadoes and Severe Weather † *May 2019*	2019-05-26	2019-05-29	A four-day tornado outbreak impacts many states across the Rockies, Central and Northeast (CO, WY, NE, KS, OK, MO, IA, IL, IN, OH, PA and NJ). This outbreak produced 190 tornadoes in addition to hundreds of reports of damaging hail and straight-line thunderstorm winds. Of particular note was an EF-4 tornado that produced heavy damage near the city of Dayton, Ohio on May 27.	$4.6 CI	3

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Central Severe Weather † *May 2019*	2019-05-16	2019-05-18	Central severe storms across the Illinois, Indiana, Iowa and Texas damaged many homes, businesses and vehicles.	$1.0 CI	0
South and Southeast Severe Weather † *May 2019*	2019-05-07	2019-05-13	Persistent severe storms impacted numerous states from Texas to North Carolina (TX, OK, KS, AR, LA, MS, AL, NC). Tornadoes and damaging hail particularly affected Texas, Louisiana and North Carolina focused across the Raleigh metro region.	$1.6 CI	0
Southern and Eastern Tornadoes and Severe Weather † *April 2019*	2019-04-13	2019-04-14	Tornado outbreak and severe storms impacted many states (TX, LA, MS, AL, GA, NC, OH and PA). More than 50 tornadoes occurred across central Mississippi and Alabama causing damage to vehicles, homes and businesses. More than 25 additional tornadoes also caused damage across several eastern states from Georgia to Pennsylvania. These severe storms also delivered damaging hail and high wind damage that was widespread across many Southern and and Eastern states.	$1.3 CI	7
Missouri River and North Central Flooding † *March 2019*	2019-03-14	2019-03-31	Historic Midwest flooding inundated millions of acres of agriculture, numerous cities and towns, and caused widespread damage to roads, bridges, levees, and dams. The states most affected were Nebraska, Iowa, Missouri, South Dakota, Minnesota, North Dakota, Wisconsin and Michigan. This flood was triggered by a powerful storm with heavy precipitation that intensified snow melt and flooding. Of note, the Offutt Air Force Base in Nebraska was also severely flooded - the third U.S. military base to be damaged by a billion-dollar disaster event over a 6-month period (Sept 2018-Feb 2019). This historic flooding was one of the costliest U.S. inland flooding events on record.	$11.0 CI	3
Texas Hail Storm † *March 2019*	2019-03-22	2019-03-24	Texas hail storm over the Dallas metroplex damaged many homes, businesses and vehicles. Oklahoma also received hail damage resulting from the same severe weather system.	$1.6 CI	0
Southeast, Ohio Valley and Northeast Severe Weather † *February 2019*	2019-02-23	2019-02-25	Tornadoes, severe weather and flooding in the south (MS, AL, TN) and high-wind damage across many Ohio Valley (IL, IN, OH) and Northeastern states (CT, MD, MA, NJ, NY, PA, VA, WV). This storm system produced heavy rain that caused major flooding along parts of the Ohio, Mississippi and Tennessee rivers.	$1.3 CI	2
Western Wildfires, California Firestorm † *Summer-Fall 2018*	2018-06-01	2018-12-31	In 2018, California has experienced its costliest, deadliest and largest wildfires to date, with records back to 1933. The Camp Fire is the costliest and deadliest wildfire - destroying more than 18,500 buildings. California also endured its largest wildfire on record - the Medincino Complex Fire - burning over 450,000 acres. Additionally, California was impacted by other destructive wildfires: the Carr Fire in Northern California and the Woolsey Fire in Southern California. The total 2018 wildfire costs in California (with minor costs in other Western states) approach $24.0 ($25.0) billion - a new U.S. record. In total, over 8.7 million acres has burned across the U.S. during 2018, which is well above the 10-year average (2009-2018) of 6.8 million acres. The last 2 years of U.S. wildfire damage has been unprecedented in damage, with losses exceeding $40.0 ($41.6) billion.	$25.0 CI	106
Southwest/ Southern Plains Drought † *Summer-Fall 2018*	2018-06-01	2018-12-30	Drought conditions were present across numerous Southwestern and Plains states (TX, OK, KS, MO, CO, NM, AZ, UT). The most extreme drought conditions continue to persist across the Four Corners region of the Southwest. The agriculture sector has been impacted across the affected states including damage to field crops from lack of rainfall. Ranchers have also be forced to sell-off livestock early in some regions due to high feeding costs.	$3.1 CI	0

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Hurricane Michael † *October 2018*	2018-10-10	2018-10-11	Powerful category 5 hurricane made landfall at Mexico Beach, Florida with devastating winds of 160 mph and storm surge in excess of 15 feet. Mexico Beach was nearly destroyed, while Panama City suffered extensive damage. Florida's Tyndall Air Force Base also suffered a direct strike from Michael's most intense eye wall winds causing billions in damage costs. Michael's intense winds also reached well inland causing billions in damage costs to agriculture and forestry, as high winds hit during harvest season for numerous crops across several states. Michael is the third category 4 or higher storm to make landfall in the U.S. since 2017. Michael is the first category 5 to strike the U.S. mainland since Hurricane Andrew in 1992 and is only the fourth on record. The others are the Labor Day Hurricane (1935) and Hurricane Camille (1969). Michael was initially rated as a category 4 with 155 winds but upgraded to a category 5 with 160 mph winds upon further analysis.	$26.0 CI	49
Hurricane Florence † *September 2018*	2018-09-13	2018-09-16	Hurricane Florence was a large and very slow moving hurricane that produced extreme rainfall across eastern North Carolina (up to 35.93") and South Carolina (up to 23.81"), as prodigious amounts of rainfall were common in many locations. Florence made landfall as a category 1, at Wrightsville Beach, NC with damaging storm surge up to 10 feet and wind gusts reported over 100 mph. However, the majority of the damage caused by Florence was due to the rainfall inland, which caused many rivers to surpass previous record flood heights. U.S. Marine base Camp Lejeune in North Carolina suffered extensive damage that will cost billions to repair. The total damage from Florence in North Carolina is more than the cost experienced during Hurricane Matthew (2016) and Hurricane Floyd (1999) combined.	$25.0 CI	53
Rockies and Plains Hail Storms † *August 2018*	2018-08-06	2018-08-07	Severe hail impacts from baseball to softball size impacted several states including Colorado, Nebraska and Wyoming. The most costly impacts occurred in numerous locations of eastern Colorado.	$1.1 CI	0
Central and Eastern Tornadoes and Severe Weather † *July 2018*	2018-07-19	2018-07-22	At least 41 tornadoes and high wind damage from thunderstorms impact numerous Central and Eastern states (MO, IA, IL, IN, KS, KY, AL, AR, GA, TN, NC, SC, VA, MD, PA) over a multi-day event. The tornado damage was most severe across Iowa.	$1.6 CI	0
Colorado Hail Storm † *June 2018*	2018-06-18	2018-06-19	Severe hail storms cause golf ball to baseball-sized hail and widespread damage in many areas from northern Denver to Boulder and Fort Collins. Many homes, businesses and vehicles were impacted. Utah also experienced moderate hail damage.	$2.3 CI	0
Texas Hail Storm † *June 2018*	2018-06-06	2018-06-06	Large-hail impacts highly-populated area of the Dallas-Ft. Worth metroplex. Golfball to baseball-sized hail damages many homes, vehicles and businesses.	$1.4 CI	0
Central and Eastern Severe Weather † *May 2018*	2018-05-13	2018-05-15	Severe storm damage across many Central states including TX, KS, CO, OK, MO, IL, IN, IA and OH. This was followed by a derecho event across the Northeastern states of MD, NJ, NY, PA, VA, WV, MA and CT that caused widespread high wind damage. Also, there were one dozen tornadoes reported across PA, NY and CT causing further damage.	$1.4 CI	5
Central and Northeastern Severe Weather † *May 2018*	2018-05-01	2018-05-04	Numerous central states (KS, NE, OK, TX, NM, MO, IA, IL, IN, OH, WI) were impacted by large hail and tornadoes. Several northeastern states including NY, PA and VT were also impacted by high wind damage from severe storms.	$1.5 CI	0
Southern and Eastern Tornadoes and Severe Weather † *April 2018*	2018-04-13	2018-04-16	Tornadoes and severe storms with large hail cause widespread damage across many Southern and Eastern states (AR, FL, GA, LA, MD, MI, MS, MO, NJ, NY, NC, PA, SC, TX, VA) over a multi-day period. There were over 70 confirmed tornadoes largely clustered in Louisiana, Mississippi, North Carolina and Virginia. This same system also caused winter storm impacts of high wind and ice accumulation in northeastern states.	$1.4 CI	3
Southeastern Tornadoes and Severe Weather † *March 2018*	2018-03-18	2018-03-21	A potent severe storm system caused over 20 tornadoes across Alabama and also widespread hail damage from Texas to Florida. Most notably this system produced an EF-3 tornado that caused extensive damage in Jacksonville, Alabama and across the campus of Jacksonville State University.	$1.5 CI	0

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Northeast Winter Storm † *March 2018*	2018-03-01	2018-03-03	Powerful Nor'easter impacted many Northeastern states including MD, MA, NH, NJ, NY, PA, CT, DE, RA and VA. Widespread damage resulted from the combination of high winds, heavy snow and heavy coastal erosion.	$2.3 CI	9
Central and Eastern Winter Storm † *January 2018*	2018-01-03	2018-01-05	A Nor'easter caused damage across many Northeastern states including MA, NJ, NY, CT, ME, NH, PA, MD, RI, SC, TN, VA, NC and GA.	$1.1 CI	22
Western Wildfires, California Firestorm † *Summer-Fall 2017*	2017-06-01	2017-12-31	A historic firestorm damages or destroys over 15,000 homes, businesses and other structures across California in October. The combined destruction of the Tubbs, Atlas, Nuns and Redwood Valley wildfires represent the most costly wildfire event on record, also causing 44 deaths. Extreme wildfire conditions in early December also burned hundreds of homes in Los Angeles. Numerous other wildfires across many western and northwestern states burn over 9.8 million acres exceeding the 10-year annual average of 6.5 million acres. Montana in particular was affected by wildfires that burned in excess of 1 million acres. These wildfire conditions were enhanced by the preceding drought conditions in several states.	$19.3 CI	54
North Dakota, South Dakota and Montana Drought † *Spring-Fall 2017*	2017-03-01	2017-12-31	Extreme drought causes extensive impacts to agriculture in North Dakota, South Dakota and Montana. Field crops including wheat were severely damaged and the lack of feed for cattle forced ranchers to sell off livestock. This drought has also contributed to the increased potential for severe wildfires.	$2.7 CI	0
Hurricane Maria † *September 2017*	2017-09-19	2017-09-21	Category 4 hurricane made landfall in southeast Puerto Rico after striking the U.S. Virgin Island of St. Croix. Maria's high winds caused widespread devastation to Puerto Rico's transportation, agriculture, communication and energy infrastructure. Extreme rainfall up to 37 inches caused widespread flooding and mudslides across the island. The interruption to commerce and standard living conditions will be sustained for a long period, as much of Puerto Rico's infrastructure is rebuilt. Maria tied Hurricane Wilma (2005) for the most rapid intensification, strengthening from tropical depression to a category 5 storm in 54 hours. Maria's landfall at Category 4 strength gives the U.S. a record three Category 4+ landfalls this year (Maria, Harvey, and Irma). Maria was one of the deadliest storms to impact the U.S., with numerous indirect deaths in the wake of the storm's devastation.	$96.3 CI	2,981
Hurricane Irma † *September 2017*	2017-09-06	2017-09-12	Category 4 hurricane made landfall at Cudjoe Key, Florida after devastating the U.S. Virgin Islands - St John and St Thomas - as a category 5 storm. The Florida Keys were heavily impacted, as 25% of buildings were destroyed while 65% were significantly damaged. Severe wind and storm surge damage also occurred along the coasts of Florida and South Carolina. Jacksonville, FL and Charleston, SC received near-historic levels of storm surge causing significant coastal flooding. Irma maintained a maximum sustained wind of 185 mph for 37 hours, the longest in the satellite era. Irma also was a category 5 storm for longer than all other Atlantic hurricanes except Ivan in 2004.	$53.5 CI	97
Hurricane Harvey † *August 2017*	2017-08-25	2017-08-31	Category 4 hurricane made landfall near Rockport, Texas causing widespread damage. Harvey's devastation was most pronounced due to the large region of extreme rainfall producing historic flooding across Houston and surrounding areas. More than 30 inches of rainfall fell on 6.9 million people, while 1.25 million experienced over 45 inches and 11,000 had over 50 inches, based on 7-day rainfall totals ending August 31. This historic U.S. rainfall caused massive flooding that displaced over 30,000 people and damaged or destroyed over 200,000 homes and businesses.	$133.8 CI	89
Midwest Severe Weather † *June 2017*	2017-06-27	2017-06-29	Severe hail and high wind damage impacting Nebraska, Illinois and Iowa. More than one dozen tornadoes touched down across parts of Iowa, in addition to other storm damage.	$1.5 CI	0
Midwest Severe Weather † *June 2017*	2017-06-12	2017-06-16	Severe hail, high winds and numerous tornadoes impact many states over several days including WY, TX, NE, KS, MO, IA, IL, PA, VA, NY.	$1.6 CI	0

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Minnesota Hail Storm and Upper Midwest Severe Weather † *June 2017*	2017-06-09	2017-06-11	Severe hail and high winds cause considerable damage across Minnesota and Wisconsin. The Minneapolis metro area in particular was damaged from large, destructive hail impacting many buildings and vehicles. This damage is comparable to the May 15, 1998 Minnesota hail storm that was also very costly.	$2.5 CI	0
Colorado Hail Storm and Central Severe Weather † *May 2017*	2017-05-08	2017-05-11	Hail storm and wind damage impacting several states including CO, OK, TX, NM, MO. The most costly impacts were in the Denver metro region where baseball-sized hail caused the most expensive hail storm in Colorado history, with insured losses exceeding $2.2 ($2.4) billion.	$3.6 CI	0
Missouri and Arkansas Flooding and Central Severe Weather † *May 2017*	2017-04-25	2017-05-07	A period of heavy rainfall up to 15 inches over a multi-state region in the Midwest caused historic levels of flooding along many rivers. The flooding was most severe in Missouri, Arkansas and southern Illinois where levees were breached and towns were flooded. There was widespread damage to homes, businesses, infrastructure and agriculture. Severe storms also caused additional impacts during the flooding event across a number of central and southern states.	$1.8 CI	20
South/ Southeast Severe Weather † *March 2017*	2017-03-26	2017-03-28	Large hail and high winds in Texas north of the Dallas metro region caused widespread damage to structures and vehicles. Severe storms also caused damage across several other states (OK, TN, KY, MS, AL) due to the combination of high winds, hail and tornadoes.	$2.9 CI	0
Southeast Freeze † *March 2017*	2017-03-14	2017-03-16	Severe freeze heavily damaged fruit crops across several southeastern states (SC, GA, NC, TN, AL, MS, FL, KY, VA). Mid-March freezes are not climatologically unusual in the Southeast, however many crops were blooming 3+ weeks early due to unusually warm temperatures during the preceding weeks. Damage was most severe in Georgia and South Carolina. Crops most impacted include peaches, blueberries, strawberries and apples, among others.	$1.1 CI	0
Midwest Tornado Outbreak † *March 2017*	2017-03-06	2017-03-08	Tornado outbreak and wind damage across many Midwestern states (AR, IA, IL, KS, MI, MN, MO, NE, NY, OH, WI). Missouri and Illinois were impacted by numerous tornadoes while Michigan and New York were affected by destructive, straight-line winds following the storm system. Nearly one million customers lost power in Michigan alone due to sustained high winds, which affected several states from Illinois to New York.	$2.4 CI	2
Central/ Southeast Tornado Outbreak † *March 2017*	2017-02-28	2017-03-01	Over 70 tornadoes developed during a widespread outbreak across many central and southern states causing significant damage. There was also widespread straight-line wind and hail damage. This was the second largest tornado outbreak to occur early in 2017.	$2.0 CI	6
California Flooding † *February 2017*	2017-02-08	2017-02-22	Heavy, persistent rainfall across northern and central California created substantial property and infrastructure damage from flooding, landslides and erosion. Notable impacts include severe damage to the Oroville Dam spillway, which caused a multi-day evacuation of 188,000 residents downstream. Excessive rainfall also caused flood damage in the city of San Jose, as Coyote Creek overflowed its banks and inundated neighborhoods forcing 14,000 residents to evacuate.	$1.6 CI	5
Southern Tornado Outbreak and Western Storms † *January 2017*	2017-01-20	2017-01-22	High wind damage occurred across southern California near San Diego followed by 79 confirmed tornadoes during an outbreak across many southern states including AL, FL, GA, LA, MS, SC and TX. This was the 3rd most tornadoes to occur in a single outbreak of extreme weather during a winter month (Dec.-Feb.) based on records from 1950.	$1.2 CI	24
Western/ Southeast Wildfires † *Summer-Fall 2016*	2016-06-01	2016-12-31	Western and Southern states experienced an active wildfire season with over 5.0 million acres burned nationally. Most notable was the firestorm that impacted Gatlinburg, Tennessee with hurricane-force wind gusts in extremely dry conditions creating volatile wildfire behavior. These wildfires destroyed nearly 2,500 structures and caused 14 fatalities. The drought conditions in many areas of the Southeast and California worsened the wildfire potential.	$2.7 CI	21

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West/ Northeast/ Southeast Drought † *2016*	2016-01-01	2016-12-31	California's 5-year drought persisted during 2016 while new areas of extreme drought developed in states across the Northeast and Southeast. The long-term impacts of the drought in California have damaged forests where 100+ million trees have perished and are a public safety hazard. The agricultural impacts were reduced in California as water prices and crop fallowing declined. However, agricultural impacts developed in Northeast and Southeast due to stressed water supplies.	$3.8 CI	0
Hurricane Matthew † *October 2016*	2016-10-08	2016-10-12	Category 1 hurricane made landfall in North Carolina, after it paralleled the Southeast coast along Florida, Georgia and the Carolinas causing widespread damage from wind, storm surge and inland flooding. The most costly impacts were due to historic levels of river flooding in eastern North Carolina where 100,000 homes, businesses and other structures were damaged. This inland flooding was comparable to Hurricane Floyd (1999) that also impacted eastern North Carolina. Matthew narrowly missed landall on Florida's east coast as a powerful category 4 storm.	$11.1 CI	49
Louisiana Flooding *August 2016*	2016-08-12	2016-08-15	A historic flood devastated a large area of southern Louisiana resulting from 20 to 30 inches of rainfall over several days. Watson, Louisiana received an astounding 31.39 inches of rain from the storm. Two-day rainfall totals in the hardest hit areas have a 0.2% chance of occurring in any given year: a 1 in 500 year event. More than 30,000 people were rescued from the floodwaters that damaged or destroyed over 50,000 homes, 100,000 vehicles and 20,000 businesses. This is the most damaging U.S. flood event since Superstorm Sandy impacted the Northeast in 2012.	$11.1 CI	13
Rockies and Northeast Severe Weather † *July 2016*	2016-07-28	2016-07-30	Severe storms across the Rockies and Northeastern states (CO, WY, VA, MD, PA, NJ, NY) caused large hail and high wind damage. Storm damage in Colorado was the most costly due to hail.	$1.6 CI	0
West Virginia Flooding and Ohio Valley Tornadoes *June 2016*	2016-06-22	2016-06-24	Torrential rainfall caused destructive flooding through many West Virginia towns, damaging thousands of homes and businesses and causing considerable loss of life. Over 1,500 roads and bridges were damaged or destroyed making the impact on infrastructure comparable to the historic 2013 Colorado flood. The storm system also produced numerous tornadoes causing damage across several Ohio Valley states.	$1.1 CI	23
Rockies/ Central Tornadoes and Severe Weather † *May 2016*	2016-05-21	2016-05-26	Sustained period of severe thunderstorms and tornadoes affecting several states including Montana, Colorado, Kansas, Missouri and Texas. The most concentrated days for tornado development were on May 22 and 24. Additional damage was created by straight-line high wind and hail damage.	$1.3 CI	0
Plains Tornadoes and Central Severe Weather † *May 2016*	2016-05-08	2016-05-11	Tornadoes and severe storms cause widespread damage across the Plains and Central states (NE, MO, TX, OK, KS, CO, IL, KY, TN) over a multi-day period. The damage from tornadoes and high wind was most costly in Nebraska and Missouri.	$1.9 CI	2
South/ Southeast Tornadoes † *April 2016*	2016-04-26	2016-05-02	Large outbreak of tornadoes affects numerous states across the South and Southeast. Additional damage also from large hail and straight-line wind during the multi-day thunderstorm event.	$2.7 CI	6
Houston Flooding † *April 2016*	2016-04-17	2016-04-18	A period of extreme rainfall up to 17 inches created widespread urban flooding in Houston and surrounding suburbs. Thousands of homes and businesses were damaged and more than 1,800 high water rescues were conducted. This represents the most widespread flooding event to affect Houston since Tropical Storm Allison in 2001.	$3.0 CI	8
North/ Central Texas Hail Storm † *April 2016*	2016-04-10	2016-04-12	Widespread severe hail damage across north and central Texas including the cities of Plano, Wylie, Frisco, Allen and San Antonio. The damage in San Antonio was particularly severe as the National Weather Service verified reports of hail size reaching 4.5 inches in diameter. This ranks as one of the most costly hail events to affect the United States.	$3.9 CI	0

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North Texas Hail Storm † *March 2016*	2016-03-23	2016-03-24	Large hail and strong winds caused considerable damage in heavily populated areas of north Texas. This damage was most notable in the cities of Dallas, Fort Worth and Plano.	$2.3 CI	0
Southern Severe Weather † *March 2016*	2016-03-17	2016-03-18	Severe hail impacts the Fort Worth and Arlington metro region in Texas. Additional large hail and high wind damage occurred in other locations of Texas, Louisiana and Mississippi.	$1.3 CI	1
Texas and Louisiana Flooding † *March 2016*	2016-03-08	2016-03-12	Multiple days of heavy rainfall averaging 15 to 20 inches led to widespread flooding along the Sabine River basin on the Texas and Louisiana border. This prompted numerous evacuations, high-water rescues and destruction, as more than 1,000 homes and businesses were damaged or destroyed.	$2.5 CI	5
Southeast and Eastern Tornadoes † *February 2016*	2016-02-22	2016-02-24	Early outbreak of tornadoes and severe weather across many southern and eastern states including (AL, CT, FL, GA, LA, MA, MD, MS, NC, NJ, NY, PA, SC, TX, VA). There were at least 50 confirmed tornadoes causing widespread damage.	$1.2 CI	10
Western Drought † *2015*	2015-01-01	2015-12-31	Drought conditions were present across numerous western states (CA, NV, OR, WA, ID, MT, UT, AZ) with the most severe conditions continuing to plague California for all of 2015. The agriculture sector was again impacted by a lack of rainfall resulting in hundreds of thousands of acres of farmland remaining fallow and requiring excess groundwater pumping to irrigate existing agriculture interests. Wildfire conditions were further enhanced by the ongoing drought. California experienced extensive damage from both drought and wildfire impacts. Drought conditions did improve dramatically across Texas and Oklahoma, in the form of several major flood events.	$5.0 CI	0
Texas Tornadoes and Midwest Flooding † *December 2015*	2015-12-26	2015-12-29	A powerful storm system packing unseasonably strong tornadoes caused widespread destruction in the Dallas metropolitan region, damaging well over 1,000 homes and businesses. This same potent system also produced intense rainfall over several Midwestern states triggering historic flooding that has approached or broken records at river gauges in several states (MO, IL, AR, TN, MS, LA). The flooding has overtopped levees and caused damage in numerous areas. This historic storm also produced high wind, snow and ice impacts from New Mexico through the Midwest and into New England. Overall, the storm caused at least 50 deaths from the combined impact of tornadoes, flooding and winter weather.	$2.2 CI	50
Western and Alaskan Wildfires † *Summer-Fall 2015*	2015-06-01	2015-11-30	Wildfires burned over 10.1 million acres across the U.S. in 2015, surpassing 2006 for the highest annual total of U.S. acreage burned since record-keeping began in 1960. The most costly wildfires occurred in California where over 2,500 structures were destroyed due to the Valley and Butte wildfires with the insured losses alone exceeding $1.0 ($1.1) billion. The most extensive wildfires occurred in Alaska where over 5 million acres burned within the state. There was extensive burnt acreage across other western states, most notably (OR, WA, ID, MT, ND, CO, WY, TX).	$3.4 CI	12
South Carolina and East Coast Flooding † *October 2015*	2015-10-01	2015-10-05	Historic levels of flooding impacted South Carolina causing widespread damage to many homes, businesses, public buildings and infrastructure. This interrupted commerce and closed major transportation corridors (such as I-95) for weeks as rivers slowly receded. Locally extreme rainfall totals exceeding 20-inches were common resulting from the convergence of a powerful low pressure system / frontal boundary and copious moisture from Hurricane Joaquin in the Atlantic.	$2.3 CI	25
Central and Northeast Severe Weather † *June 2015*	2015-06-21	2015-06-25	Severe storms across numerous Central and Northeast states (CO, CT, IA, IL, MD, MI, NJ, NY, PA, SD, VA, WI) with widespread hail and high wind damage.	$1.3 CI	1
Texas and Oklahoma Flooding and Severe Weather † *May 2015*	2015-05-23	2015-05-26	A slow-moving system caused tremendous rainfall and subsequent flooding to occur in Texas and Oklahoma. The Blanco river in Texas swelled from 5 feet to a crest of more than 40 feet over several hours causing considerable property damage and loss of life. The city of Houston also experienced flooding which resulted in hundreds of high-water rescues. The damage in Texas alone exceeded $1.0 ($1.1) billion. There was also damage in other states (KS, CO, AR, OH, LA, GA, SC) from associated severe storms.	$2.8 CI	31

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
Southern Plains Tornadoes † *May 2015*	2015-05-06	2015-05-10	Tornado outbreak across the Southern Plain states (IA, KS, NE, OK, CO, SD, TX) with 122 tornadoes. The most costly damage occurred across Texas and Oklahoma.	$1.4 CI	4
South and Southeast Severe Weather † *April 2015*	2015-04-24	2015-04-25	Severe weather produced tornadoes, large hail and high wind damage across numerous southern and southeastern states including Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi and Texas. These storms caused widespread impacts to many homes, vehicles and businesses.	$1.0* CI	3
South/ Southeast Severe Weather † *April 2015*	2015-04-18	2015-04-20	Severe storms across the South and Southeastern states (AL, AR, FL, GA, KS, LA, MS, NC, OK, SC, TN, TX). High winds and severe hail created the most significant damage in Texas.	$1.5 CI	0
Midwest/ Ohio Valley Severe Weather † *April 2015*	2015-04-07	2015-04-09	Severe storms across the Midwest and Ohio Valley including the states (AR, IA, IL, IN, KS, KY, MI, MO, NC, OH, OK, PA, TN, TX, WI, WV). Large hail and high winds created the most damage across Missouri and Illinois.	$1.8 CI	2
Central and Eastern Winter storm, Cold Wave † *February 2015*	2015-02-14	2015-02-20	A large winter storm and associated cold wave impacted many central, eastern and northeastern states (CT, DE, GA, IL, KY, MA, MD, ME, MI, NC, NH, NJ, NY, OH, PA, RI, SC, TN, VA). The city of Boston was particularly impacted as feet of snow continued to accumulate causing load-stress on buildings and clogging transportation corridors. Total, direct losses in Massachusetts alone exceed $1.0 ($1.1) billion for this event, with considerable damage in many other states.	$3.3 CI	30
Western Drought † *2014*	2014-01-01	2014-12-31	Historic drought conditions affected the majority of California for all of 2014 making it the worst drought on record for the state. Surrounding states and parts of Texas, Oklahoma and Kansas also experienced continued severe drought conditions. This is a continuation of drought conditions that have persisted for several years.	$4.4 CI	0
Rockies/ Plains Severe Weather † *September 2014*	2014-09-29	2014-10-02	Severe storms across the Rockies and Plains states (CO, KS, TX). Large hail and high winds created significant damage across eastern Colorado and Texas, particularly in the Dallas metro area.	$1.6 CI	0
Michigan and Northeast Flooding † *August 2014*	2014-08-11	2014-08-13	Heavy rainfall in excess of 5 inches caused significant flooding in cities across Michigan damaging thousands of cars, business, homes and other infrastructure. Flooding also occurred across Maryland and New York's Long Island, as the slow-moving storm system delivered 24-hour rainfall exceeding 6 and 12 inches, respectively, creating more flood damage. Islip, NY received 13.57 inches of rain over a 24-hour period on Aug 12-13 setting a new 24-hour precipitation record for New York.	$1.2 CI	2
Rockies/ Central Plains Severe Weather † *June 2014*	2014-06-03	2014-06-05	Severe storms across the Rockies and Central Plains states (NE, KS, WY, IA, AR). Wind gusts exceeding 90 mph and baseball to softball sized hail caused severe damage to structures and vehicles in central and eastern Nebraska.	$2.1 CI	2
Rockies/ Midwest/ Eastern Severe Weather † *May 2014*	2014-05-18	2014-05-23	Severe storms across the Rockies, Midwest and Eastern states (CO, MT, IA, IL, IN, OH, SC, VA, PA, DE, NY) with the most costly damage in Colorado, Illinois and Pennsylvania.	$4.2 CI	0
Midwest/ Southeast/ Northeast Tornadoes and Flooding † *April 2014*	2014-04-27	2014-05-01	Tornado outbreak across the Midwest, Southeast and Northeast states (AL, AR, DE, FL, GA, KS, MD, MO, MS, NC, NJ, NY, PA, TN, VA) with 83 confirmed tornadoes. Mississippi had its 3rd greatest number of tornadoes reported for any day since 1950. Torrential rainfall in the Florida panhandle also caused major flooding, as Pensacola set new 1-day and 2-day precipitation records of 15.55 and 20.47 inches, respectively. Flooding rains were also reported in coastal Alabama, as Mobile received 11.24 inches of rain, the third greatest calendar day rainfall total for the city.	$1.9 CI	33

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
Central Severe Weather † *April 2014*	2014-04-12	2014-04-13	Severe weather produced hail and high wind damage across several central states including Illinois, Iowa, Michigan, Wisconsin and Texas. The damage was most focused in Illinois and Michigan, as storms caused impacts to many homes, vehicles and businesses.	$1.0* CI	0
Plains Severe Weather † *April 2014*	2014-04-02	2014-04-03	Severe storms across the Plains states (IL, KS, MO, TX) causing considerable hail and wind damage in Texas.	$1.6 CI	0
Midwest/ Southeast/ Northeast Winter Storm † *January 2014*	2014-01-05	2014-01-08	Winter storm caused widespread damage across numerous Midwest, Southeast and Northeastern states (AL, GA, IL, IN, KY, MD, MI, MO, MS, NC, NJ, NY, OH, PA, SC, TN, VA).	$2.4 CI	16
Western/ Plains Drought/ Heatwave † *Spring-Fall 2013*	2013-03-01	2013-11-30	The 2013 drought slowly dissipated from the historic levels of the 2012 drought, as conditions improved across many Midwestern and Plains states. However, moderate to extreme drought did remain or expand into western states (AZ, CA, CO, IA, ID, IL, KS, MI, MN, MO, ND, NE, NM, NV, OK, OR, SD, TX, UT, WA, WI, WY). In comparison to 2011 and 2012 drought conditions the US experienced only moderate crop losses across the central agriculture states.	$11.9 CI	53
Ohio Valley Tornadoes † *November 2013*	2013-11-17	2013-11-17	Late-season outbreak of tornadoes and severe weather over the Ohio Valley (IL, IN, KY, MI, MO, OH) with 70 confirmed tornadoes. Most severe impacts occurred across Illinois and Indiana.	$1.2 CI	8
Colorado Flooding *September 2013*	2013-09-10	2013-09-16	A stalled frontal boundary over Colorado led to record rainfall, as some areas received > 15 inches over several days. This resulted in historic flooding across numerous cities and towns. Destruction of residences, businesses and transportation infrastructure was widespread.	$1.7 CI	9
Midwest Severe Weather † *August 2013*	2013-08-06	2013-08-07	Severe weather and large hail causes considerable damage across Minnesota and Wisconsin.	$1.2 CI	0
Midwest/ Plains/ Northeast Tornadoes † *May 2013*	2013-05-27	2013-05-31	Outbreak of tornadoes and severe weather over the Midwest, Plains and Northeast (IL, IN, KS, MO, NY, OK, TX) with 92 confirmed tornadoes including the deadly tornado that struck El Reno, OK. There was also significant damage resulting from hail and straight-line wind.	$2.1 CI	10
Midwest/ Plains/ East Tornadoes † *May 2013*	2013-05-18	2013-05-22	Outbreak of tornadoes and severe weather over the Midwest, Plains and Eastern states (GA, IA, IL, KS, MO, NY, OK, TX) with 59 confirmed tornadoes including the deadly tornado that impacted Moore, OK. Many destructive tornadoes remained on the ground for an extended time.	$2.7 CI	27
Illinois Flooding and Severe Weather † *April 2013*	2013-04-16	2013-04-19	A slow-moving storm system created rainfall totals of 5 to 10 inches across northern and central Illinois including the Chicago metro. This resulted in damage to many homes and businesses. There was also severe weather damage from wind and hail across Indiana and Missouri.	$1.2 CI	4
Midwest/ Plains Severe Weather † *April 2013*	2013-04-07	2013-04-11	Severe weather across the Midwest and Plains states (IN, KS, MO, NE) with a total of 26 confirmed tornadoes. Considerable damage resulting from hail and straight-line wind.	$1.6 CI	1
Southeast Severe Weather † *March 2013*	2013-03-18	2013-03-18	Severe weather over the Southeast (MS, AL, GA, TN) with 10 confirmed tornadoes. Considerable damage resulting from large hail and straight-line wind.	$2.3 CI	1

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Southern Severe Weather † *February 2013*	2013-02-24	2013-02-25	Severe weather produced severe hail and wind damage across several southern states including Louisiana, Oklahoma and Texas. The damage was most focused in Louisiana near New Orleans, as severe hail caused significant damage costs to many homes, vehicles and businesses.	$1.0* CI	1
U.S. Drought/ Heatwave † *2012*	2012-01-01	2012-12-31	The 2012 drought is the most extensive drought to affect the U.S. since the 1930s. Moderate to extreme drought conditions affected more than half the country for a majority of 2012. The following states were affected: CA, NV, ID, MT, WY, UT, CO, AZ, NM, TX, ND, SD, NE, KS, OK, AR, MO, IA, MN, IL, IN, GA. Costly drought impacts occurred across the central agriculture states resulting in widespread harvest failure for corn, sorghum and soybean crops, among others. The associated summer heatwave also caused 123 direct deaths, but an estimate of the excess mortality due to heat stress is still unknown.	$34.8 CI	123
Western Wildfires † *Summer-Fall 2012*	2012-06-01	2012-11-30	Wildfires burned over 9.2 million acres across the U.S. in 2012. This is the 3rd highest annual total since the year 2000. The most damaging wildfires occurred in the western states (CO, ID, WY, MT, CA, NV, OR, WA). Colorado experienced the most costly wildfires (e.g., Waldo Canyon fire) where several hundred residences were destroyed.	$2.0 CI	8
Hurricane Sandy *October 2012*	2012-10-30	2012-10-31	Extensive damage across several northeastern states (MD, DE, NJ, NY, CT, MA, RI) due to high wind and coastal storm surge, particularly NY and NJ. Damage from wind, rain and heavy snow also extended more broadly to other states (NC, VA, WV, OH, PA, NH), as Sandy merged with a developing Nor'easter. Sandy's impact on major population centers caused widespread interruption to critical water / electrical services and also caused 159 deaths (72 direct, 87 indirect). Sandy also caused the New York Stock Exchange to close for two consecutive business days, which last happened in 1888 due to a major winter storm.	$75.4 CI	159
Hurricane Isaac *August 2012*	2012-08-26	2012-08-31	Category 1 hurricane made landfall over Louisiana. Isaac's slow motion and large size led to a large storm surge and flooding rains. This created damage across several southeastern states (LA, MS, AL, FL) including 9 deaths (5 direct, 4 indirect).	$3.2 CI	9
Plains/ East/ Northeast Severe Weather † *June-July 2012*	2012-06-29	2012-07-02	Sustained outbreak of thunderstorms / high winds from a strong derecho event over the central, eastern, and northeastern states (IL, IN, KY, OH, WV, SC, NC, VA, MD, DC, NJ).	$3.4 CI	28
Rockies/ Southwest Severe Weather † *June 2012*	2012-06-06	2012-06-12	Severe storms and damaging hail over several states (CO, NM, TX) with 25 confirmed tornadoes. Colorado experienced over $1.0 ($1.2) billion in damage due to hail.	$3.0 CI	0
Southern Plains/ Midwest/ Northeast Severe Weather † *May 2012*	2012-05-25	2012-05-30	Severe storms over the southern plains, midwest and northeast (TX, OK, KS, MN, PA, NY) with 27 confirmed tornadoes. Significant damage also from severe hail and straight-line winds.	$2.7 CI	1
Midwest/ Ohio Valley Severe Weather † *April-May 2012*	2012-04-28	2012-05-01	Severe weather over the midwest and Ohio Valley (TX, OK, KS, MO, IL, IN, KY) with 38 confirmed tornadoes. Considerable damage resulting from hail.	$3.8 CI	1
Midwest Tornadoes † *April 2012*	2012-04-13	2012-04-14	Outbreak of tornadoes and severe weather over the midwest (OK, KS, NE, IA) with 98 confirmed tornadoes including many tornadoes that remained on the ground for an extended time - traveling tens of miles.	$1.3 CI	6
Texas Tornadoes † *April 2012*	2012-04-02	2012-04-03	Outbreak of tornadoes across the greater Dallas-Ft. Worth metropolitan area. Several moderate strength tornadoes (EF-2 and EF-3) affected towns in this area with a total of 22 confirmed tornadoes.	$1.2 CI	0

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Southeast/ Ohio Valley Tornadoes † *March 2012*	2012-03-02	2012-03-03	Outbreak of tornadoes and severe weather over the southeast and Ohio Valley (AL, GA, IN, OH, KY, TN) with 75 confirmed tornadoes.	$3.6 CI	42
Texas, New Mexico, Arizona Wildfires † *Summer-Fall 2011*	2011-06-01	2011-11-30	Continued drought conditions and periods of extreme heat provided conditions favorable for a series of historic wildfires across Texas, New Mexico and Arizona. The Bastrop Fire in Texas was the most destructive fire in Texas history destroying over 1,500 homes. The Wallow Fire consumed over 500,000 acres in Arizona making it the largest on record in Arizona. The Las Conchas Fire in New Mexico was also the state's largest wildfire on record scorching over 150,000 acres while threatening the Los Alamos National Laboratory. Over 3 million acres have burned across Texas this wildfire season.	$2.2 CI	5
Tropical Storm Lee † *September 2011*	2011-09-01	2011-09-05	Wind and flood damage across the southeast (LA, MS, AL, GA, TN) but considerably more damage from record flooding across the northeast (PA, NY, NJ, CT, VA, MD). Pennsylvania and New York were most affected.	$3.0 CI	21
Southern Plains/ Southwest Drought & Heat Wave † *Spring-Summer 2011*	2011-03-01	2011-08-31	Drought and heat wave conditions created major impacts across Texas, Oklahoma, New Mexico, Arizona, southern Kansas, and western Louisiana. In Texas and Oklahoma, a majority of range and pastures were classified in "very poor" condition for much of the 2011 crop growing season.	$14.2 CI	95
Hurricane Irene † *August 2011*	2011-08-26	2011-08-28	Category 1 hurricane made landfall over coastal NC and moved northward along the Mid-Atlantic Coast (NC, VA, MD, NJ, NY, CT, RI, MA, VT) causing torrential rainfall and flooding across the Northeast. Wind damage in coastal NC, VA, and MD was moderate with considerable damage resulting from falling trees and power lines, while flooding caused extensive flood damage across NJ, NY, and VT. Over seven million homes and businesses lost power during the storm. Numerous tornadoes were also reported in several states further adding to the damage.	$16.1 CI	45
Midwest/ Southeast Severe Weather † *August 2011*	2011-08-17	2011-08-18	Severe weather impacts the states IA, KS, MO, NE, SD across the Midwest and Southeast.	$1.4 CI	0
Rockies and Midwest Severe Weather † *July 2011*	2011-07-10	2011-07-14	An outbreak of tornadoes, hail, and high wind caused damage east of the Rockies and across the central plains (CO, WY, IA, IL, MI, MN, OH).	$1.5 CI	2
Missouri River flooding † *May-June 2011*	2011-05-01	2011-06-30	Melting of an above-average snow pack across the Northern Rocky Mountains combined with above-average precipitation caused the Missouri and Souris Rivers to swell beyond their banks across the Upper Midwest (MT, ND, SD, NE, IA, KS, MO). An estimated 11,000 people were forced to evacuate Minot, North Dakota due to the record high water level of the Souris River, where 4,000 homes were flooded. Numerous levees were breached along the Missouri River, flooding thousands of acres of farmland.	$2.4 CI	5
Midwest/ Southeast Tornadoes and Severe Weather † *June 2011*	2011-06-18	2011-06-22	Outbreak of tornadoes over central states (OK, TX, KS, NE, MO, IA, IL) with an estimated 81 tornadoes. Additional wind and hail damage across the Southeast (TN, GA, NC, SC).	$1.8 CI	3
Mississippi River flooding † *April-May 2011*	2011-04-01	2011-05-31	Persistent rainfall (nearly 300 percent normal precipitation amounts in the Ohio Valley) combined with melting snowpack caused historical flooding along the Mississippi River and its tributaries. Examples of economic damage include: $500 ($595.0) million to agriculture in Arkansas; $320 ($380.8) million in damage to Memphis, Tennessee; $800 ($952.0) million to agriculture in Mississippi; $317 ($377.2) million to agriculture and property in Missouri's Birds Point-New Madrid Spillway; $80 ($95.2) million for the first 30 days of flood fighting efforts in Louisiana.	$3.6 CI	7

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Midwest/ Southeast Tornadoes † *May 2011*	2011-05-22	2011-05-27	Outbreak of tornadoes over central and southern states (MO, TX, OK, KS, AR, GA, TN, VA, KY, IN, IL, OH, WI, MN, PA) with an estimated 180 tornadoes. Notably, an EF-5 tornado struck Joplin, MO resulting in at least 160 deaths, making it the deadliest single tornado to strike the U.S. since modern tornado record keeping began in 1950.	$10.8 CI	177
Southeast/ Ohio Valley/ Midwest Tornadoes *April 2011*	2011-04-25	2011-04-28	Outbreak of tornadoes over central and southern states (AL, AR, LA, MS, GA, TN, VA, KY, IL, MO, OH, TX, OK) with an estimated 343 tornadoes. The deadliest tornado of the outbreak, an EF-5, hit northern Alabama, killing 78 people. Several major metropolitan areas were directly impacted by strong tornadoes including Tuscaloosa, Birmingham, and Huntsville in Alabama and Chattanooga, Tennessee, causing the estimated damage costs to soar.	$12.2 CI	321
Ohio Valley/ South Tornadoes † *April 2011*	2011-04-19	2011-04-20	Dozens of tornadoes and severe storms affect the states AR, IL, IN, KY, MO, OH, TN, TX across the Ohio Valley and South.	$1.2 CI	0
Midwest/ Southeast Tornadoes † *April 2011*	2011-04-14	2011-04-16	Outbreak of tornadoes over central and southern states (OK, TX, AR, MS, AL, GA, NC, SC, VA, PA) with an estimated 177 tornadoes.	$2.5 CI	38
Southeast/ Midwest Tornadoes † *April 2011*	2011-04-08	2011-04-11	Outbreak of tornadoes over central and southern states (NC, SC, TN, AL, TX, OK, KS, IA, WI) with an estimated 59 tornadoes.	$2.6 CI	0
Midwest/ Southeast Tornadoes † *April 2011*	2011-04-04	2011-04-05	Outbreak of tornadoes over central and southern states (KS, MO, IA, IL, WI, KY, GA, TN, NC, SC) with an estimated 46 tornadoes.	$3.3 CI	9
Groundhog Day Blizzard † *February 2011*	2011-02-01	2011-02-03	A large winter storm impacted many central, eastern and northeastern states. The city of Chicago was brought to a virtual standstill as between 1 and 2 feet of snow fell over the area.	$2.1 CI	36
Arizona Severe Weather *October 2010*	2010-10-05	2010-10-06	An unusual series of severe thunderstorms across Arizona produced numerous tornadoes and widespread, severe hail damage. Over one-hundred buildings were damaged or destroyed by tornadoes while thousands of automobiles and buildings were damaged by large hail across Phoenix and surrounding cities.	$4.6 CI	0
Midwest/ Northeast Severe Storms and Flooding † *July 2010*	2010-07-20	2010-07-23	Severe storms and flooding affect the states IA, IL, MD, NY, PA, WI across the Midwest and Northeast.	$1.1* CI	0
Rockies/ Central/ East Severe Weather † *June 2010*	2010-06-10	2010-06-15	Severe storms cause high wind and hail damage across numerous states including CO, NM, KS, OK, IL, IN, GA, SC and NC.	$1.1* CI	2
Oklahoma, Kansas, and Texas Tornadoes and Severe Weather † *May 2010*	2010-05-10	2010-05-12	An outbreak of tornadoes, hail, and severe thunderstorms occurred across Oklahoma, Kansas, and Texas in mid-May. Oklahoma was hardest hit with > $1.5 ($1.8) billion in damages.	$4.0 CI	3

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East/ South Flooding and Severe Weather † *May 2010*	2010-04-30	2010-05-02	Flooding, hail, tornadoes, and severe thunderstorms occurred across many Southern states (TN, AR, KY, GA) on April 30-May 2. Flooding in the Nashville, TN area alone contributed > $1.0 ($1.2) billion in damages. Western and Middle Tennessee were hardest hit with local rainfall amounts of 18-20 inches to the south and west of Greater Nashville.	$2.7 CI	32
Northeast Flooding † *March 2010*	2010-03-01	2010-03-31	Heavy rainfall over portions of the Northeast in late March caused extensive flooding across several states (RI, CT, MA, NJ, NY, PA). The event caused the worst flooding in Rhode Island's history.	$2.2 CI	11
Northeast Winter Storm † *February 2010*	2010-02-09	2010-02-11	Winter storm produced 10-20 inches of snow and high wind impacts across numerous northeastern and eastern states including Pennsylvania, Maryland, Delaware, New Jersey, West Virginia, Virginia and North Carolina. These impacts were most focused in Pennsylvania and Maryland, as this winter storm closely followed a previous winter storm from the week prior.	$1.0* CI	3
Southwest/ Great Plains Drought † *2009*	2009-01-01	2009-12-31	Drought conditions occurred during much of the year across parts of the Southwest, Great Plains, and southern Texas causing agricultural losses in numerous states (TX, OK, KS, CA, NM, AZ). The largest agriculture losses occurred in TX and CA.	$4.4 CI	0
Western Wildfires † *Summer-Fall 2009*	2009-06-01	2009-11-30	Residual and sustained drought conditions across western and south-central states resulted in thousands of wildfires. Most affected states include CA, AZ, NM, TX, OK, and UT. National acreage burned exceeding 5.9 million. Over 200 homes and structures destroyed in the California "Station" fire alone.	$1.3 CI	10
Colorado Hail Storm † *July 2009*	2009-07-20	2009-07-20	Severe hail impacts Colorado. Jefferson County was most affected with hail at least 8 inches deep. The hail damage from this storm was comparable to the July 11, 1990 Colorado hail storm.	$1.3 CI	0
Midwest, South and East Severe Weather † *June 2009*	2009-06-09	2009-06-12	Sustained outbreak of thunderstorms and high winds from a strong derecho event over the central, southern, and eastern states (TX, OK, MO, NE, KS, AR, AL, MS, TN, NC, SC, KY, PA).	$1.7 CI	0
Central Tornadoes and Severe Weather † *May 2009*	2009-05-07	2009-05-09	More than 50 tornadoes and large hail from severe storms caused damage across many southeastern states (IL, KS, KY, MO, TN, TX).	$1.1* CI	7
South/ Southeast Severe Weather & Tornadoes † *April 2009*	2009-04-09	2009-04-10	Outbreak of tornadoes, hail and severe thunderstorms over the south and southeastern states (AL, AR, GA, KY, MO, SC, TN) with 85 confirmed tornadoes.	$1.8 CI	6
Midwest/ Southeast Tornadoes † *March 2009*	2009-03-25	2009-03-28	Outbreak of tornadoes over central and southern states (NE, KS, OK, IA, TX, LA, MS, AL, GA, TN, KY) with 56 tornadoes confirmed.	$2.1 CI	0
Southeast/ Ohio Valley Severe Weather † *February 2009*	2009-02-10	2009-02-11	Complex of severe thunderstorms and high winds across the region (TN, KY, OK, OH, VA, WV, PA).	$2.2 CI	10
U.S. Drought † *2008*	2008-01-01	2008-12-31	Severe drought and heat caused agricultural losses across a large portion of the U.S. Record low lake levels also occurred in areas of the southeast. The states impacted include AL, AR, CA, CO, GA, ID, IN, KS, KY, MD, MN, MS, MT, NC, ND, NJ, NM, OH, OK, OR, SC, TN, TX, UT, VA, WA and WI.	$8.8 CI	0

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U.S. Wildfires † *Fall 2008*	2008-09-01	2008-11-30	Drought conditions across numerous western, central and southeastern states (AK, AZ, CA, NM, ID, UT, MT, NV, OR, WA, CO, TX, OK, NC, FL) resulted in thousands of wildfires; national acreage burned exceeding 5.2 million acres (mainly in the west) and over 1,000 homes and structures destroyed in California fires alone.	$1.5 CI	16
Hurricane Ike † *September 2008*	2008-09-12	2008-09-14	Category 2 hurricane makes landfall in Texas, as the largest (in size) Atlantic hurricane on record, causing considerable storm surge in coastal TX and significant wind and flooding damage in TX, LA, AR, TN, IL, IN, KY, MO, OH, MI and PA. Severe gasoline shortages occurred in the southeast U.S. due to damaged oil platforms, storage tanks, pipelines and off-line refineries.	$37.5 CI	112
Hurricane Gustav † *September 2008*	2008-08-31	2008-09-03	Category 2 hurricane makes landfall in Louisiana causing significant wind, storm surge, and flooding damage in AL, AR, LA, and MS.	$7.5 CI	53
Hurricane Dolly † *July 2008*	2008-07-23	2008-07-25	Category 2 hurricane makes landfall in southern Texas causing considerable wind and flooding damage in TX and NM.	$1.6 CI	3
Midwest Flooding *Summer 2008*	2008-04-01	2008-06-30	Heavy rain and flooding caused significant agricultural loss and property damage in IA, IL, IN, MO, MN, NE, and WI with IA being hardest hit with widespread rainfall totals ranging from 4 to over 16 inches.	$12.4 CI	24
Midwest/ Mid-Atlantic Severe Weather † *June 2008*	2008-06-06	2008-06-12	An outbreak of tornadoes and thunderstorms over the Midwest/Mid-Atlantic states (IA, IL, IN, KS, NE, MI, MN, MO, OK, WI, MD, VA, WV).	$2.0 CI	18
Midwest Tornadoes and Severe Weather † *May 2008*	2008-05-22	2008-05-27	Outbreak of tornadoes over the Midwest/Ohio Valley regions (IL, IN, IA, KS, MN, NE, OK, WY, CO) with 235 tornadoes confirmed.	$3.8 CI	13
Southern Severe Weather † *April 2008*	2008-04-09	2008-04-11	Severe storms affect Arkansas, Oklahoma and Texas across the South.	$1.3 CI	2
Southeast Tornadoes † *March 2008*	2008-03-14	2008-03-15	Tornadoes and severe weather across Georgia and South Carolina. This includes an EF-2 tornado causing damage to numerous buildings in downtown Atlanta.	$1.4 CI	5
Southeast Tornadoes and Severe Weather † *February 2008*	2008-02-05	2008-02-06	Series of tornadoes and severe thunderstorms across the Southeast and Midwest states (AL, AR, IN, KY, MS, OH, TN, TX) with 87 tornadoes confirmed.	$1.5 CI	57
Western, Central and Northeast Severe Weather † *January 2008*	2008-01-04	2008-01-09	Strong storm produces severe weather including hail, high winds and heavy precipitation from California to New York. Flash floods and landslides cause damage in California. In addition, more than 70 tornadoes were reported from Arkansas to Wisconsin, with the highest concentration of tornadoes in Missouri.	$1.2 CI	12
Western/ Eastern Drought/ Heatwave † *Summer-Fall 2007*	2007-06-01	2007-11-30	Severe drought with periods of extreme heat over most of the southeast and portions of the Great Plains, Ohio Valley, and Great Lakes area, resulting in major reductions in crop yields, along with very low stream-flows and lake levels. Includes states of ND, SD, NE, KS, OK, TX, MN, WI, IA, MO, AR, LA, MS, AL, GA, NC, SC, FL, TN, VA, WV, KY, IN, IL, OH, MI, PA, NY.	$4.6 CI	15

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Western Wildfires † *Summer 2007*	2007-06-01	2007-08-31	Continued drought conditions and high winds over much of the western U.S. (AK, AZ, CA, ID, UT, MT, NV, OR, WA) resulting in numerous wildfires; with national acreage burned exceeding 8.9 million acres (mainly in the west) and over 3,000 homes and structures destroyed in southern California alone.	$3.6 CI	12
East/ South Severe Weather and Flooding † *April 2007*	2007-04-13	2007-04-17	Flooding, hail, tornadoes, and severe thunderstorms across numerous states (CT, DE, GA, LA, ME, MD, MA, MS, NH, NJ, NY, NC, PA, RI, SC, TX, VT, VA) in mid-April, including 3 "killer" tornadoes.	$3.3 CI	9
Spring Freeze *April 2007*	2007-04-04	2007-04-10	Widespread severe freeze over much of the east and midwest (AL, AR, GA, IA, IL, IN, KS, KY, MO, MS, NC, NE, OH, OK, SC, TN, VA, WV), causing significant losses in fruit crops, field crops (especially wheat), and the ornamental industry. Temperatures in the teens/20s accompanied by rather high winds nullified typical crop-protection systems.	$2.7 CI	0
California Freeze † *January 2007*	2007-01-11	2007-01-17	Widespread agricultural freeze -- for nearly two weeks in January, overnight temperatures over a good portion of California dipped into the 20s, destroying numerous agricultural crops; with citrus, berry, and vegetable crops most affected.	$1.8 CI	1
Numerous Wildfires † *2006*	2006-01-01	2006-12-31	Numerous wildfires driven by dry weather and high winds burned over 9.8 million acres, across the western half of the country including Alaska. This is the second highest annual total behind the 10.1 million acres burned in 2015 since record-keeping began in 1960. The most affected states were AK, AZ, CA, CO, FL, ID, MT, NM, NV, OK, OR, TX, WA, WY	$2.0 CI	28
Central Severe Weather † *October 2006*	2006-10-02	2006-10-05	Severe storms cause high wind and hail damage across numerous states including OH, IL, IN, MI, MN and WI.	$1.2* CI	1
Midwest/ Plains/ Southeast Drought † *Spring-Summer 2006*	2006-03-01	2006-08-31	Rather severe drought affected crops especially during the spring-summer, centered over the Great Plains region with other areas affected across portions of the south -- including states of ND, SD, NE, KS, OK, TX, MN, IA, MO, AR, LA, MS, AL, GA, FL, MT, WY, CO, NM.	$8.0 CI	0
Northeast Flooding † *June 2006*	2006-06-25	2006-06-28	Severe flooding over portions of the northeast due to several weeks of heavy rainfall, affecting the states of NY, PA, DE, MD, NJ, and VA.	$2.0 CI	20
Midwest Tornadoes † *April 2006*	2006-04-13	2006-04-16	Tornadoes and severe weather cause significant damage in the states of IA, IL, IN, and WI. The state of Indiana was most affected with over one billion dollars in damage.	$3.2 CI	27
Midwest/ Southeast Tornadoes † *April 6-8, 2006*	2006-04-06	2006-04-08	Severe weather and numerous tornadoes affecting the states of OK, KS, MO, NE, KY, OH, TN, IN, MS, GA, and AL on April 6-8 with 3 "killer" tornadoes in TN.	$2.1 CI	10
Severe Storms and Tornadoes *March 2006*	2006-03-08	2006-03-13	Outbreak of tornadoes over portions of the midwest and south during a week-long period- affecting the states of AL, AR, KY, MS, TN, TX, IN, KS, MO, and OK.	$1.8 CI	10
Hurricane Wilma † *October 2005*	2005-10-24	2005-10-24	Category 3 hurricane hits SW Florida resulting in strong damaging winds and major flooding across southeastern Florida. Prior to landfall, Wilma as a Category 5 recorded the lowest pressure (882 mb) ever recorded in the Atlantic basin.	$26.2 CI	35
Hurricane Rita † *September 2005*	2005-09-20	2005-09-24	Category 3 hurricane hits Texas-Louisiana border coastal region, creating significant storm surge and wind damage along the coast, and some inland flooding in the FL panhandle, AL, MS, LA, AR, and TX. Prior to landfall, Rita reached the third lowest pressure (897 mb) ever recorded in the Atlantic basin.	$25.5 CI	119

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
Midwest Drought † *Spring-Summer 2005*	2005-03-01	2005-08-31	Rather severe localized drought causes significant crop losses (especially for corn and soybeans) in the states of AR, IL, IA, IN, MO, OH, and WI.	$2.0 CI	0
Hurricane Katrina *August 2005*	2005-08-25	2005-08-30	Category 3 hurricane initially impacts the U.S. as a Category 1 near Miami, FL, then as a strong Category 3 along the eastern LA-western MS coastlines, resulting in severe storm surge damage (maximum surge probably exceeded 30 feet) along the LA-MS-AL coasts, wind damage, and the failure of parts of the levee system in New Orleans. Inland effects included high winds and some flooding in the states of AL, MS, FL, TN, KY, IN, OH, and GA.	$172.5 CI	1,833
Hurricane Dennis † *July 2005*	2005-07-09	2005-07-11	Category 3 hurricane makes landfall in western Florida panhandle resulting in storm surge and wind damage along the FL and AL coasts, along with scattered wind and flood damage in GA and MS.	$3.4 CI	15
Southeast Severe Weather † *March 2005*	2005-03-24	2005-03-27	Severe storms cause widespread hail damage across numerous states including TX, AL, MS, GA, FL, NC and VA.	$1.2* CI	0
Hurricane Jeanne † *September 2004*	2004-09-15	2004-09-29	Category 3 hurricane makes landfall in east-central Florida, causing considerable wind, storm surge, and flooding damage in FL, with some flood damage also in the states of GA, SC, NC, VA, MD, DE, NJ, PA, and NY. Puerto Rico also affected.	$10.6 CI	28
Hurricane Ivan † *September 2004*	2004-09-12	2004-09-21	Category 3 hurricane makes landfall on Gulf coast of Alabama, with significant wind, storm surge, and flooding damage in coastal AL and FL panhandle, along with wind/flood damage in the states of GA, MS, LA, SC, NC, VA, WV, MD, TN, KY, OH, DE, NJ, PA, and NY.	$29.1 CI	57
Hurricane Frances † *September 2004*	2004-09-03	2004-09-09	Category 2 hurricane makes landfall in east-central Florida, causing significant wind, storm surge, and flooding damage in FL, along with considerable flood damage in the states of GA, SC, NC, and NY due to 5-15 inch rains.	$13.9 CI	48
Hurricane Charley † *August 2004*	2004-08-13	2004-08-14	Category 4 hurricane makes landfall in southwest Florida, resulting in major wind and some storm surge damage in FL, along with some damage in the states of SC and NC.	$22.7 CI	35
Severe Storms, Hail, Tornadoes † *May 2004*	2004-05-21	2004-05-27	Severe storms including tornadoes and hail cause damage across the Midwest, South, Southeast and Northeast regions. The states impacted include IA, IL, IN, KY, MI, MO, NC, NE, NY, OK, OH and WI.	$1.4 CI	4
California Wildfires † *Fall 2003*	2003-09-01	2003-11-30	Dry weather, high winds, and resulting wildfires in Southern California burned over 3,700 homes. Nearly 4.0 million acres burned across numerous western states including Alaska.	$5.6 CI	22
Western/ Central Drought/ Heatwave † *Spring-Fall 2003*	2003-03-01	2003-11-30	2003 drought across western and central portions of the U.S. with losses to agriculture. The states most impacted include AZ, CO, IA, ID, IL, KS, MI, MN, MO, MT, ND, NE, NM, OR, SD, WA and WI.	$7.3 CI	35
Hurricane Isabel † *September 2003*	2003-09-18	2003-09-19	Category 2 hurricane makes landfall in eastern North Carolina, causing considerable storm surge damage along the coasts of NC, VA, and MD, with wind damage and some flooding due to 4-12 inch rains in NC, VA, MD, DE, WV, NJ, NY, and PA.	$8.0 CI	55
Severe Weather † *July 2003*	2003-07-21	2003-07-23	Severe storms impact states across the South, Southeast, Midwest and Northeast regions. The states most impacted include AR, AL, MS, GA, FL, SC, TN, KY, MI, NY, OH, PA and VT.	$1.5 CI	7

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Midwest/ Plains Severe Weather † *July 2003*	2003-07-04	2003-07-09	Severe storms affect the states IA, IL, IN, MI, MN, OH, VA, WV across the Midwest and Plains.	$1.2* CI	7
Severe Storms/ Tornadoes † *May 2003*	2003-05-03	2003-05-10	Numerous tornadoes over the midwest, Mississippi valley, OH/TN valleys, and portions of the southeast, with a modern record one-week total of approximately 400 tornadoes reported	$6.0 CI	51
Severe Storms/ Hail † *April 2003*	2003-04-04	2003-04-07	Severe storms and large hail over the southern plains and lower MS valley, with Texas hardest hit, and much of the monetary losses due to hail.	$2.9 CI	3
Western Fire Season † *Fall 2002*	2002-09-01	2002-11-30	Major wildfires over 11 western states from the Rockies to the west coast due to drought and periodic high winds, with over 7.1 million acres burned.	$2.0 CI	21
U.S. Drought † *Spring-Fall 2002*	2002-03-01	2002-11-30	Moderate to extreme drought over large portions of more than 30 states, including the western states, the Great Plains, and much of the eastern U.S.	$13.4 CI	0
Eastern Tornadoes and Severe Storms † *November 2002*	2002-11-09	2002-11-11	Tornado outbreak of over 100 tornadoes across many eastern states causes widespread damage (AL, MS, GA, TN, KY, OH, PA). Tennessee and Ohio had the highest count of tornadoes.	$1.0* CI	28
Tropical Storm Isidore † *September 2002*	2002-09-25	2002-09-27	Tropical Storm Isidore caused heavy rain, flooding, tornadoes and coastal storm surge that impacted Louisiana, Mississippi, Alabama and Tennessee. Rainfall exceeded 15 inches across southern Louisiana with storm surge over 8 feet.	$1.7 CI	5
Hurricane Lili *October 2002*	2002-08-01	2002-08-05	Category 1 hurricane makes landfall in Louisiana after causing damage across Saint Lucia, Jamaica, Haiti and Cuba.	$1.6 CI	2
Severe Storms and Tornadoes *April 2002*	2002-04-27	2002-04-28	Numerous tornadoes and widespread hail damage over the Central and Eastern states including NC, GA, VA, TX, AR, MO, MS, TN, IL, IN, KY, PA, MD, NY, OH, WV, and KS.	$3.1 CI	7
Tropical Storm Allison *June 2001*	2001-06-05	2001-06-17	The persistent remnants of Tropical Storm Allison produce rainfall amounts of 30-40 inches in portions of coastal Texas and Louisiana, causing severe flooding especially in the Houston area, then moves slowly northeastward; fatalities and significant damage reported in TX, LA, MS, FL, VA, and PA	$12.8 CI	43
Midwest/ Ohio Valley Hail and Tornadoes *April 2001*	2001-04-06	2001-04-11	Storms, tornadoes, and hail in the states of TX, OK, KS, NE, IA, MO, IL, IN, WI, MI, OH, KY, WV, and PA, over a 6-day period.	$4.6 CI	3
Western/ Central/ Southeast Drought/ Heatwave † *Spring-Fall 2000*	2000-03-01	2000-11-30	Western/Central/Southeast Drought/Heatwave. The states impacted include AZ, AL, AR, CA, CO, FL, GA, IA, KS, LA, MS, MT, NE, NM, OK, OR, SC, TN, and TX.	$7.8 CI	140

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South Florida Flooding *October 2000*	2000-10-03	2000-10-04	Heavy rainfall up to 15 inches affected south Florida surrounding Miami that resulted in severe flooding that damaged thousands of homes and businesses. There was also several hundred million in damage done to agriculture.	$1.4* CI	3
Western Fire Season † *Spring-Summer 2000*	2000-03-01	2000-08-31	Severe wildfire season in the western states due to drought and frequent winds, with nearly 7 million acres burned.	$1.7 CI	0
Southern Severe Weather † *March 2000*	2000-03-28	2000-03-29	Severe weather produced tornadoes, hail and high wind damage across Louisiana and Texas. The damage was most focused in northeastern Texas. These storms caused impacts to many homes, vehicles and businesses.	$1.1* CI	0
Southeast Winter Storm † *January 2000*	2000-01-21	2000-01-24	Strong winter storm causes disruption and damage over numerous southeastern states (AL, GA, NC, SC, TN, LA, VA). Record amounts of snowfall occured across central North Carolina, with snow totals in excess of 20 inches.	$1.1* CI	4
Hurricane Floyd *September 1999*	1999-09-14	1999-09-16	Large, category 2 hurricane makes landfall in eastern NC, causing 10-20 inch rains in 2 days, with severe flooding in NC and some flooding in SC, VA, MD, PA, NY, NJ, DE, RI, CT, MA, NH, and VT.	$10.4 CI	77
Eastern Drought/ Heatwave † *Summer 1999*	1999-06-01	1999-08-31	Very dry summer and high temperatures, mainly in eastern U.S., with extensive agricultural losses. The states impacted include AL, AR, FL, GA, KY, LA, MD, MS, NC, NJ, OH, SC, TN, VA, WV and PA.	$4.0 CI	502
Oklahoma and Kansas Tornadoes *May 1999*	1999-05-03	1999-05-06	Outbreak of F4-F5 tornadoes hit the states of Oklahoma and Kansas, along with Texas and Tennessee, Oklahoma City area hardest hit.	$3.2 CI	55
Central and Eastern Winter Storm *Mid-January 1999*	1999-01-13	1999-01-16	Winter storm affecting the Central and Eastern states including IL, IN, OH, MI, WV, VA, MD, PA, NJ, NY, MA, CT, VT, NH and ME.	$1.4* CI	0
Central and Eastern Winter Storm *January 1999*	1999-01-01	1999-01-04	South, Southeast, Midwest, Northeast affected by damaging winter storm	$1.7 CI	25
California Freeze *December 1998*	1998-12-20	1998-12-28	A severe freeze damaged fruit and vegetable crops in the Central and Southern San Joaquin Valley. Extended intervals of sub 27° F temperatures occurred over an 8-day period.	$4.1 CI	0
Texas Flooding *October 1998*	1998-10-16	1998-10-24	Severe flooding in southeast Texas from 2 heavy rain events, with 10-20 inch rainfall totals	$1.5* CI	31
Hurricane Georges *September 1998*	1998-09-20	1998-09-29	Category 2 hurricane strikes Puerto Rico, Virgin Islands, Florida Keys, and Gulf coasts of Louisiana, Mississippi, Alabama, and Florida panhandle, 15-30 inch 2-day rain totals in parts of Alabama and Florida	$9.8 CI	16

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Southern Drought/ Heat Wave *Summer 1998*	1998-06-01	1998-08-31	Severe drought and heat wave from Texas/Oklahoma eastward to the Carolinas. The states impacted include AL, AR, FL, GA, LA, MS, NC, OK, SC, TN, TX, and VA.	$5.8 CI	200
Hurricane Bonnie *August 1998*	1998-08-27	1998-08-29	Category 3 hurricane strikes eastern North Carolina and Virginia, extensive agricultural damage due to winds and flooding, with 10-inch rains in 2 days in some locations.	$1.6 CI	3
Tropical Storm Frances *September 1998*	1998-08-08	1998-08-13	Tropical Storm Frances caused extensive flooding in Texas and Louisiana. The rainfall totals from Frances were 10 to 20 inches across eastern Texas into southern Louisiana.	$1.1* CI	2
Severe Storms, Tornadoes *June 1998*	1998-05-30	1998-06-02	Severe storms in late May through early June hit the Midwest, North, Northeast, and Southeast	$1.9 CI	20
Minnesota Severe Storms/ Hail *May 1998*	1998-05-15	1998-05-15	Very damaging severe thunderstorms with large hail over wide areas of Minnesota	$2.7 CI	1
Western/ Eastern Severe Weather and Flooding *Winter-Spring 1998*	1997-12-01	1998-02-28	Tornadoes and flooding cause damage across the West and Southeast. The states impacted include CA, TX, FL, AL, GA, LA, MS, NC and SC.	$1.7 CI	132
Northeast Ice Storm *January 1998*	1998-01-05	1998-01-09	Intense ice storm hits Maine, New Hampshire, Vermont, and New York, with extensive forestry losses	$2.3 CI	16
Northern Plains Flooding *Spring 1997*	1997-02-03	1997-05-24	Severe flooding in North Dakota, South Dakota and Minnesota due to heavy spring snow melt. This flooding caused widespread damage to agriculture, infrastructure, homes and businesses.	$6.1 CI	11
Mississippi and Ohio Valley Severe Weather and Flooding *March 1997*	1997-02-28	1997-03-05	Tornadoes and severe flooding hit the states of AR, MO, MS, TN, IL, IN, KY, OH, and WV, with over 10 inches of rain in 24 hours in Louisville.	$1.6 CI	67
West Coast Flooding *December 1996-January 1997*	1997-01-01	1997-01-11	Torrential rains (10-40 inches in 2 weeks) and snowmelt produce severe flooding over portions of CA, WA, OR, ID, NV, and MT.	$5.0 CI	36
Hurricane Fran *September 1996*	1996-09-05	1996-09-08	Category 3 hurricane strikes North Carolina and Virginia, over 10-inch 24-hour rains in some locations and extensive agricultural and other losses.	$8.5 CI	37

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Southern Plains Drought *Spring-Summer 1996*	1996-03-01	1996-08-31	Severe drought in agricultural regions of southern plains--Texas and Oklahoma most severely affected	$3.0 CI	0
Pacific Northwest Severe Flooding *February 1996*	1996-02-07	1996-02-12	Very heavy, persistent rains (10-30 inches) and melting snow over OR, WA, ID, and western MT.	$1.7 CI	9
Blizzard/ Floods *January 1996*	1996-01-01	1996-01-31	Very heavy snowstorm (1-4 feet) over Appalachians, Mid-Atlantic, and Northeast; followed by severe flooding in parts of same area due to rain and snowmelt.	$5.1 CI	187
Hurricane Opal *October 1995*	1995-10-04	1995-10-06	Category 3 hurricane strikes Florida panhandle, Alabama, western Georgia, eastern Tennessee, and the western Carolinas, causing storm surge, wind, and flooding damage.	$8.2 CI	27
Central, Southern and Northeast Drought/ Heatwave † *September 1995*	1995-07-01	1995-09-30	Historic mid-July heatwave and urban heat island amplification caused hundreds of deaths across several major cities including Chicago, Milwaukee, and Philadelphia. Following the heat wave was hot, dry weather in July and August 1995 that affected crops in numerous states, as crops had not rooted well due to late planting from previous wet soils. This left crops vulnerable to a flash drought during a key portion of the growing season.	$1.7 CI	872
Hurricane Marilyn *September 1995*	1995-09-15	1995-09-17	Category 2 hurricane impacts the U.S. Virgin Islands and Puerto Rico with maximum sustained winds of 110 mph.	$3.7 CI	13
Hurricane Erin *August 1995*	1995-08-01	1995-08-07	Hurricane Erin impacted Florida as a category 1 hurricane. Most of the damage resulted from heavy rainfall and flooding in Florida, Alabama and Mississippi.	$1.5* CI	6
South Plains Severe Weather *May 1995*	1995-05-05	1995-05-07	Torrential rains, hail, and tornadoes across Texas-Oklahoma and southeast Louisiana-southern Mississippi, with Dallas and New Orleans areas (10-25 inch rains in 5 days) hardest hit.	$9.6 CI	32
California Flooding *January-March 1995*	1995-01-01	1995-03-31	Frequent winter storms cause 20-70 inch rainfall and periodic flooding across much of California	$4.4 CI	27
Western Fire Season *Summer-Fall 1994*	1994-06-01	1994-11-30	Severe wildfire season in the western states due to dry weather conditions. The states most impacted include CA, AZ, OR, WA, CO, UT, NV, NM and TX.	$1.3* CI	0
Texas Flooding *October 1994*	1994-10-16	1994-10-25	Torrential rain (10-25 inches in 5 days) and thunderstorms cause flooding across much of southeast Texas	$1.8 CI	19
Tropical Storm Alberto *July 1994*	1994-07-07	1994-07-10	Remnants of slow-moving Alberto bring torrential 10-25 inch rains in 3 days, widespread flooding and agricultural damage in parts of Georgia, Alabama, and panhandle of Florida.	$1.8 CI	32

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Midwest/ Plains Tornadoes *April 1994*	1994-04-25	1994-04-27	Tornadoes and severe storms cause damage in states across the South, Southeast and Midwest. The states impacted include TX, OK, AR, CO, KS, NE, IA, SD, IL, IN, MN and MO.	$1.8 CI	3
Southeast Ice Storm *February 1994*	1994-02-08	1994-02-13	Intense ice storm with extensive damage in portions of TX, OK, AR, LA, MS, AL, TN, GA, SC, NC, and VA.	$5.4 CI	9
Winter Storm, Cold Wave *January 1994*	1994-01-17	1994-01-20	Winter storm affects the Southeast and Northeast regions. The states impacted include CT, DE, IL, IN, KY, MA, MD, ME, NC, NH, NJ, NY, OH, PA, RI, SC, TN, VA, VT and WV.	$1.9 CI	70
California Wildfires *Fall 1993*	1993-09-01	1993-11-30	Dry weather, high winds and wildfires in Southern California	$2.5 CI	4
Southeast Drought/ Heat Wave *Summer 1993*	1993-06-01	1993-08-31	Drought and heat wave across Southeastern U.S. The states most impacted include AL, FL, GA, MD, NC, SC, TN, and VA.	$2.3 CI	16
Midwest Flooding *Summer 1993*	1993-06-27	1993-08-15	Severe, widespread flooding in central U.S. due to persistent heavy rains and thunderstorms. There was extensive damage to agriculture, infrastructure, homes and businesses in many areas across several states. Many river stations also established new records for historical flood heights. This is the most costly non-tropical, inland flood event to affect the United States on record.	$38.6 CI	48
Northern Plains and Ohio Valley Severe Weather *July 1993*	1993-07-08	1993-07-10	Severe storms caused high wind, hail and tornado damage across many Northern/Central Plains (NE, KS, MO, IA, MN, ND) and Ohio Valley states (IL, IN).	$1.2* CI	1
East Coast Blizzard and Severe Weather *March 1993*	1993-03-11	1993-03-14	The "Storm of the Century" impacts the entire Eastern seaboard from Florida to Maine. This historic storm dumped 2-4 feet of snow and caused hurricane force winds across many Eastern and Northeastern states. This caused power outages to over 10 million households. Additional impacts included numerous tornadoes across Florida causing substantial damage. This is the most destructive and costly winter storm to affect the United States since at least 1980.	$10.2 CI	270
Northeast Winter Storm *December 1992*	1992-12-10	1992-12-13	Slow-moving winter storm batters northeast U.S. coast, with the New England region hardest hit. The states impacted include VA, MD, DE, PA, NJ, NY, CT, RI, MA and WV.	$4.7 CI	19
Southeast Severe Weather *November 1992*	1992-11-21	1992-11-23	Three-day tornado outbreak strikes many Central and Eastern states including TX, LA, AL, MS, GA, AR, IN, OH, KY, TN, and NC. Major damage was reported across many areas, as more than 100 tornadoes were reported. This event remains one of the most prolific Fall season tornado outbreaks on record.	$1.2* CI	26
Hurricane Iniki *September 1992*	1992-09-11	1992-09-12	Category 4 hurricane causes severe damage to the Hawaiian island of Kauai. Hurricane Iniki is the costliest and deadliest hurricane to affect Hawaii since 1900.	$5.9 CI	7
Hurricane Andrew *August 1992*	1992-08-23	1992-08-27	Category 5 hurricane hits Florida and later impacts Louisiana as a category 3. High winds damage or destroy over 125,000 homes and leave at least 160,000 people homeless in Dade County, Florida alone. Initially rated as a category 4, Andrew was later upgraded to a category 5 upon further analysis. Andrew joins Hurricane Camille (1969) and the Labor Day Hurricane (1935), as the only land falling category 5 hurricanes on record to affect the U.S. mainland. Adjusted to present-day dollars, Andrew is the 6th most costly hurricane to impact the U.S. since 1980, after Katrina (2005), Harvey (2017), Maria (2017), Sandy (2012) and Irma (2017).	$51.3 CI	61

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Severe Storms, Hail *June 1992*	1992-06-19	1992-06-20	Severe storms with hail hit Kansas and Oklahoma	$1.4*	0
Hail, Tornadoes *April 1992*	1992-04-28	1992-04-29	Severe Storms hit Oklahoma and Texas with tornadoes and hail	$1.8	0
Severe Storms *March 1992*	1992-03-24	1992-03-25	Severe storms affect the South, Southeast. The states most impacted include Texas, Louisiana and Florida.	$1.5*	0
Oakland Firestorm *October 1991*	1991-10-01	1991-10-31	Oakland, California firestorm due to low humidity and high winds burned over 3,000 homes. This was the costliest urban wildfire to affect the United States since 1980 when it occurred.	$6.4	25
U.S. Drought *Spring-Summer 1991*	1991-03-01	1991-08-31	Drought conditions over parts of the West, Central and eastern U.S. most affected the states IL, IN, KS, MN, OH, OR, PA, SD, and WA.	$5.9	0
Hurricane Bob *August 1991*	1991-08-18	1991-08-20	Category 2 hurricane brushes the Outer Banks of North Carolina before making landfall in Rhode Island. Its impacts were felt from North Carolina to Long Island and into New England.	$2.9	18
Severe Storms, Tornadoes *March 1991*	1991-03-26	1991-03-29	Severe storms hit the Midwest, Southeast, Northeast. The states impacted include KS, IL, MI, IN, MS, TN, KY, OH, AL, PA, NY, GA, SC and NC.	$1.3*	0
California Freeze *December 1990*	1990-12-18	1990-12-25	Severe freeze in the Central and Southern San Joaquin Valley caused the loss of citrus, avocado trees, and other crops in many areas. Several days of subfreezing temperatures occurred, with some valley locations in the teens.	$7.0	0
Colorado Hail Storm *July 1990*	1990-07-11	1990-07-11	Denver, CO (including airport) hit by severe hail storm. This was the costliest hail storm on record for Colorado when it occurred.	$1.7*	0
Southern Flooding *May 1990*	1990-05-11	1990-05-19	Torrential rains cause flooding along the Trinity, Red, and Arkansas Rivers in TX, OK, LA, and AR	$2.1	13
Winter Storm, Cold Wave *December 1989*	1989-12-21	1989-12-26	Winter storm and deep cold impacts the Northeast, South and Southeast. The states impacted include AL, AR, CT, FL, GA, IL, IN, KY, LA, ME, MO, MS, NC, NH, NY, OH, OK, PA, SC, TN, TX, VA, VT and WV.	$1.5*	100
[illegible] *December 1989*	1989-12-23	1989-12-25	Severe freeze damages citrus crops across central/northern Florida.	$4.3	10
Summer-Fall 1989	1989-06-01	1989-11-30	Severe summer drought over much of the northern plains with significant losses to agriculture. The states impacted include CO, IA, IL, KS, MO, ND, NE, NV, SD, TX and UT.	$6.5	0
September 1989	1989-09-21	1989-09-22	Category 4 hurricane devastates South and North Carolina with ~20 foot storm surge and severe wind damage after hitting Puerto Rico and the U.S. Virgin Islands	$19.5	86

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May 1989	1989-05-01	1989-05-06	Severe storms cause damage in states across the South and Southeast. The states impacted include OK, TX, LA, MS, GA, SC, NC and VA.	$1.2* CI	21
Summer 1988	1988-06-01	1988-08-31	1988 drought across a large portion of the U.S. with very severe losses to agriculture and related industries. Combined direct and indirect deaths (i.e., excess mortality) due to heat stress estimated at 5,000.	$45.4 CI	454
Summer 1986	1986-06-01	1986-08-31	Severe summer drought in parts of the southeastern U.S. with severe losses to agriculture. The states impacted include AL, AR, GA, LA, MS, NC, SC, TN and VA.	$4.3 CI	100
February 1986	1986-02-14	1986-02-16	Severe storms and flooding affect the states CA, CO, NV, OR, WY across the West.	$1.3* CI	13
November 1985	1985-11-03	1985-11-08	Historic flooding damaged or destroyed over 10,000 homes and businesses across West Virginia and Virginia. Rainfall exceeded 19 inches, which forced the Roanoke and James Rivers, among others, to record levels. The damage in Virginia was most severe in the towns of Roanoke and Richmond. In Pennsylvania, floods also damaged or destroyed several thousand homes. Maryland experiened severe but more isolated flooding and damage.	$3.4 CI	62
October 1985	1985-10-27	1985-10-31	Category 1 hurricane makes landfall near Morgan City, Louisiana. Hurricane Juan's slow movement causes severe flooding in Louisiana, Mississippi, Alabama and Florida. Southern Louisiana was most severely affected due to widespread rainfall of 10-15 inches that caused substantial flooding.	$3.7 CI	63
September 1985	1985-09-26	1985-09-28	Category 2 hurricane makes several landfalls along the eastern seaboard, affecting states from North Carolina to Maine.	$2.1* CI	11
September 1985	1985-08-30	1985-09-03	Category 3 hurricane approaches the Florida Panhandle prior to landfall near Biloxi, Mississippi. Considerable wind and rain impacts were felt from Florida to Louisiana.	$3.2 CI	4
January 1985	1985-01-20	1985-01-22	Severe freeze over central/northern Florida damages citrus crops.	$3.0 CI	0
January 1985	1985-01-19	1985-01-22	Extreme cold and winter storms in the Southeast, South, Southwest, Northeast, Midwest, and North	$2.1* CI	150
June 1984	1984-06-13	1984-06-17	Severe storms and hail impact Colorado, South Dakota and Nebraska.	$1.2* CI	1
Spring 1984	1984-03-27	1984-04-07	States in the Southeast and Northeast regions are impacted by tornadoes, severe storms, and flooding. The states impacted include GA, FL, SC, NC, VA, MD, DE, NJ, NY, PA, CT, MA and RI.	$1.6* CI	80

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST (IN BILLIONS)	DEATHS
December 1983	1983-12-15	1983-12-25	Severe freeze damages citrus crops across central/northern Florida. Associated cold wave over much of the U.S. causes over 100 deaths and additional damages.	$5.4 CI	151
Summer 1983	1983-06-01	1983-08-31	1983 flash drought in the southeastern U.S. with losses to agriculture, most notably corn and soybeans. The states impacted include AL, AR, GA, KY, LA, MO, MS, NC, SC, TN and VA.	$8.0 CI	0
August 1983	1983-08-17	1983-08-20	Category 3 hurricane makes landfall near Galveston, Texas with maximum sustained winds 115 mph. Hurricane Alicia was the first hurricane to hit the United States mainland since Hurricane Allen in August 1980.	$8.1 CI	21
December 1982-March 1983	1982-12-13	1983-03-31	Severe storms and flooding, especially in the states of WA, OR, CA, AZ, NV, ID, UT, and MT	$4.2 CI	50
December 1982-January 1983	1982-12-01	1983-01-15	Severe storms and flooding, especially in the states of TX, AR, LA, MS, AL, GA, and FL	$4.3 CI	45
June 1982	1982-05-31	1982-06-10	Severe storms cause damage across the South, Southeast and Central regions. The states impacted include AR, IL, KY, IN, SC, GA and OH.	$1.3* CI	30
April 1982	1982-04-02	1982-04-04	Tornadoes and severe weather affect the states (AL, AR, CO, IA, IL, IN, KS, KY, LA, MI, MN, MO, MS, NE, OH, OK, PA, TN, TX, WI, WV) across the Midwest, Plains and Southeast.	$1.3* CI	33
January 1982	1982-01-08	1982-01-16	Winter storm and coldwave affect numerous states (AL, AR, CT, DE, FL, GA, IA, IL, IN, KS, KY, LA, MA, MD, ME, MI, MN, MO, MS, NC, ND, NH, NJ, NY, OH, OK, PA, RI, SC, TN, TX, VA, VT, WI, WV) across the Midwest, Southeast and Northeast.	$1.8* CI	85
May 1981	1981-05-05	1981-05-10	Severe storms cause damage across the Midwest and South. The states most impacted include TX, OK, KS, AL and LA.	$1.2* CI	20
January 1981	1981-01-12	1981-01-14	Severe freeze heavily damaged fruit crops across Florida. Over 25,000 Florida farms were impacted and sustained losses.	$1.7* CI	0
Summer-Fall 1980	1980-06-01	1980-11-30	Central and eastern U.S. drought/heat wave caused damage to agriculture and other related industries. Combined direct and indirect deaths (i.e., excess mortality) due to heat stress estimated at 10,000.	$33.9 CI	1,260
August 1980	1980-08-07	1980-08-11	Category 3 hurricane makes landfall north of Brownsville, Texas with maximum sustained winds of 115 mph. Hurricane Allen causes rainfall up to 20 inches in southern Texas and storm surge as high as 12 feet along the coast.	$2.0* CI	13

EVENT	BEGIN DATE	END DATE	SUMMARY	CPI-ADJUSTED ESTIMATED COST *(IN BILLIONS)*	DEATHS
April 1980	1980-04-10	1980-04-17	Severe storms and flooding affect several states (AR, LA, MS) across the South.	$2.4* CI	7

**Exceeds $1 billion-dollar threshold after 2021 Consumer Price Index adjustment*
†Please note hyperlinked reports were compiled using preliminary data, and the statistics will not always match the latest figures presented here.

The confidence interval (CI) probabilities (75%, 90% and 95%) represent the uncertainty associated with the disaster cost estimates. Monte Carlo simulations were used to produce upper and lower bounds at these confidence levels (Smith and Matthews, 2015).

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Exhibit 3

22 Northern Great Plains

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22

Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

Northern Great Plains

Cameron, Montana

Key Message 1

Water

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

Key Message 2

Agriculture

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

Key Message 3

Recreation and Tourism

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

Key Message 4

Energy

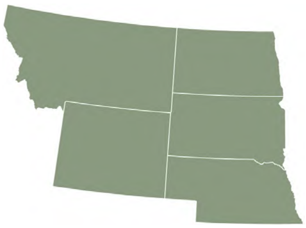
Fossil fuel and renewable energy production and distribution infrastructure is expanding within the Northern Great Plains. Climate change and extreme weather events put this infrastructure at risk, as well as the supply of energy it contributes to support individuals, communities, and the U.S. economy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

Key Message 5

Indigenous Peoples

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

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.

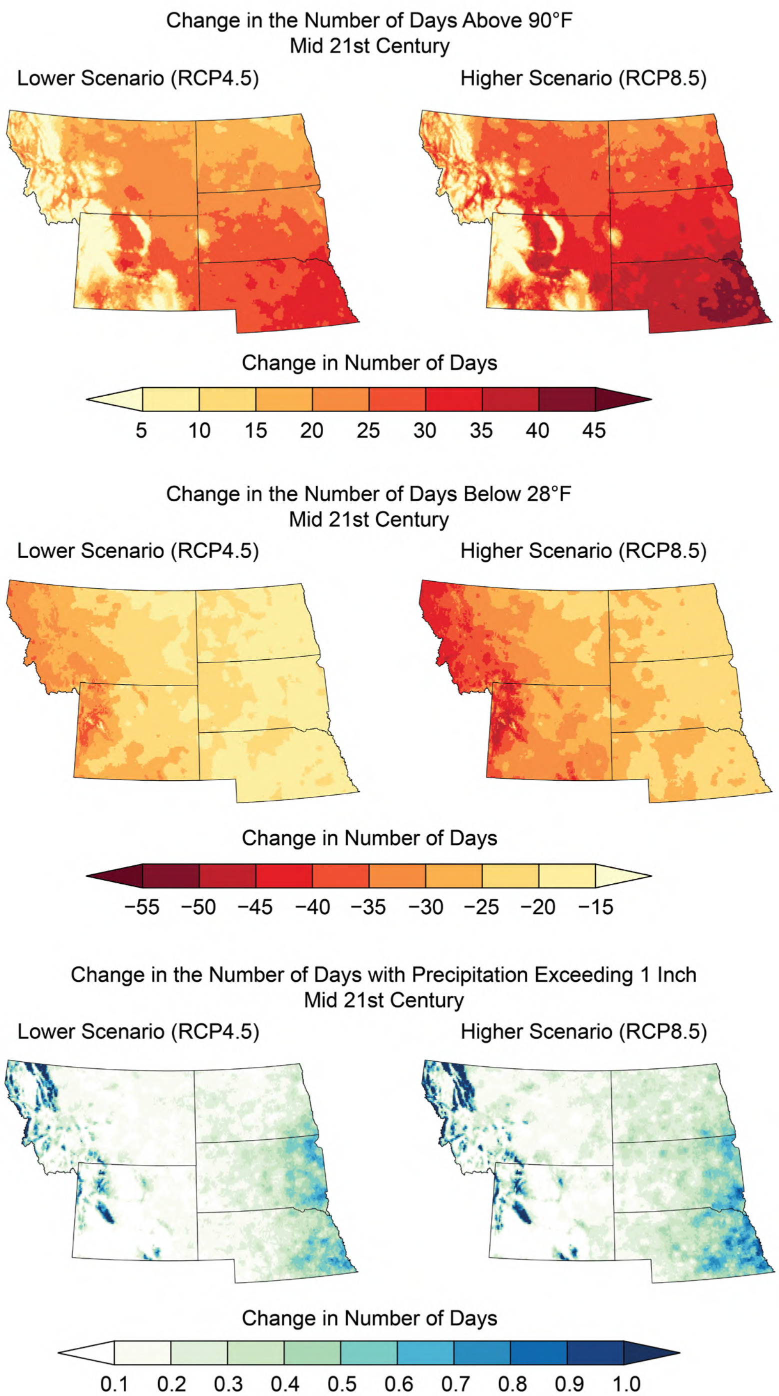
The Northern Great Plains region plays a critical role in national food security. Among other anticipated changes, projected warmer and generally wetter conditions with elevated atmospheric carbon dioxide concentrations are expected to increase the abundance and competitive ability of weeds and invasive 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 yields[6] 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]

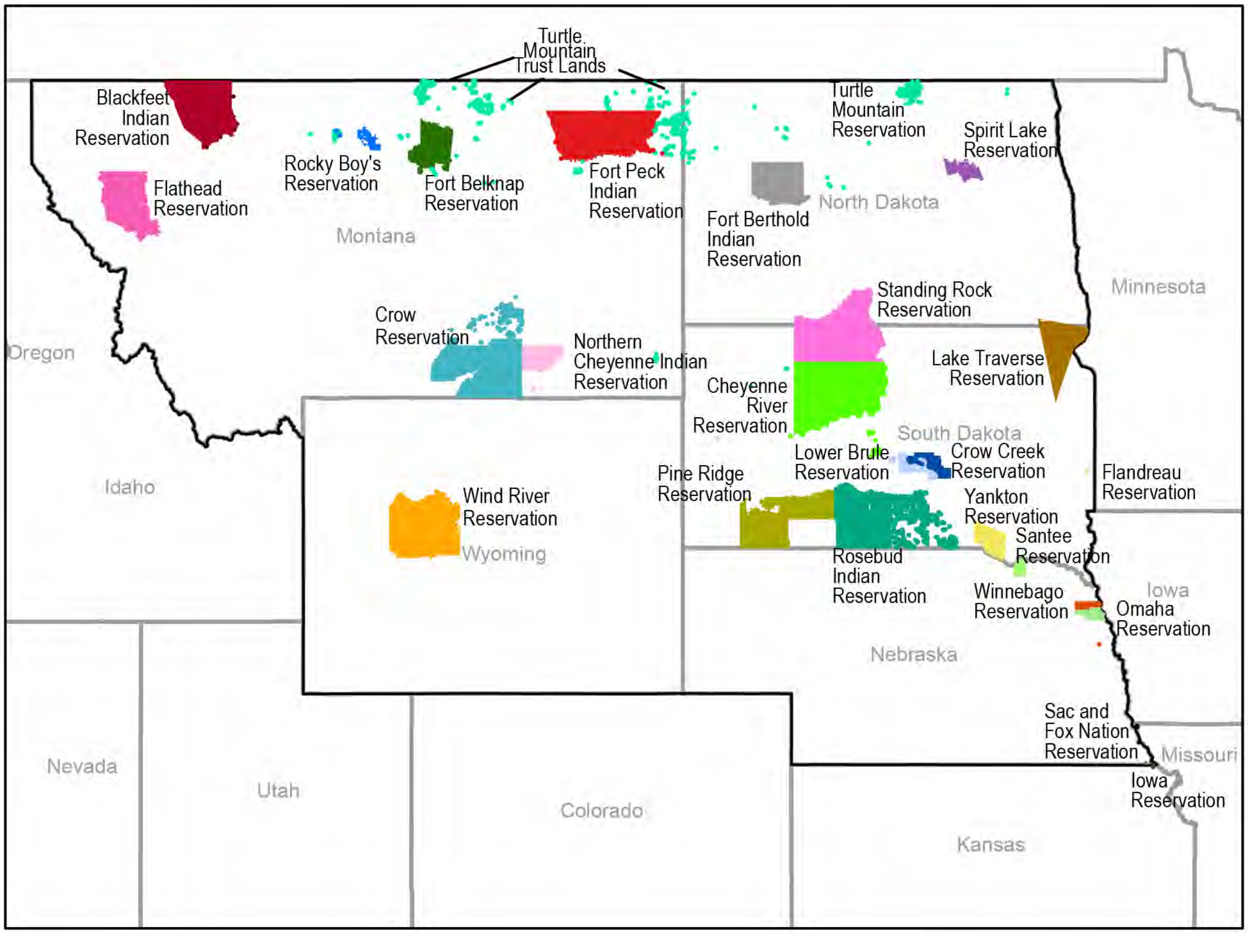
Indigenous peoples in the region are observing changes to climate, many of which are impacting livelihoods as well as traditional subsistence and wild foods, wildlife, plants and water for ceremonies, medicines, and health and well-being.[14,15,16,17,18,19,20,21,22,23,24,25,26] Because some tribes and 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 2015[32]). 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

1

Impact: Flash droughts and high heat events illustrate challenges for sustainability of ranching operations, with emergent impacts on rural prosperity and mental health.

Response: Adaptive management frameworks, developed through management–science partnerships, proactively increase flexibility in operational decision-making to reduce economic and ecological risk.

2

Impact: Consecutive years of drought across the region force ranchers to consider selling off their herds.

Response: Montana's Matador Ranch establishes a "grassbank" that allows local ranchers to pay discounted fees for access to additional grass during droughts in exchange for wildlife-friendly practices on their own operations.

3

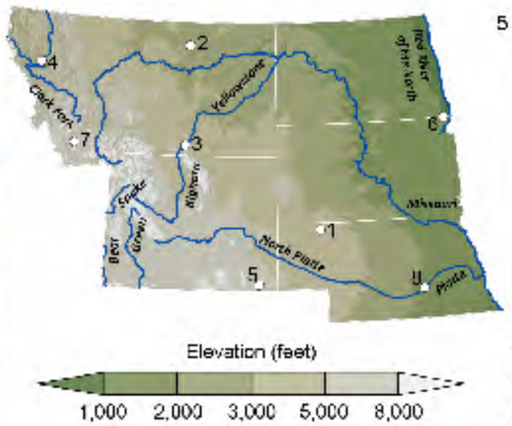
Impact: Rising temperatures hasten the spread of invasive species in riparian ecosystems, threatening culturally significant native species and food sources in the Crow Indian (Apsaalooké) Reservation.

Response: The USDA NRCS Crow Agency worked with Little Big Horn College students to remove invasive populations along the Little Big Horn River. They also revegetated plains cottonwood in sandbars and developed riparian buffer zones.

4

Impact: Anticipated climate change impacts on cultural resources raise concerns within the leadership of the Confederated Salish and Kootenai Tribes.

Response: Tribal leaders developed their climate change strategic plan to address climate impacts and vulnerabilities drawing heavily on Traditional Ecological Knowledge.



5

Impact: Greenhouse gas emissions from petroleum and natural gas production across the Northern Great Plains are among the highest in the Nation.

Response: Potential wind energy resources are among the largest in the Northern Great Plains.

6

Impact: The Prairie Pothole Region, considered the world's most productive habitat for waterfowl, is threatened by warming temperatures.

Response: The Prairie Pothole Joint Venture implements wetland and grassland protection, restoration, and enhancement projects to sustain populations of waterfowl, shorebirds, and prairie landbirds.

7

Impact: Changing runoff characteristics and increasing stream temperatures threaten water and ecological resources.

Response: The Beaverhead Drought Resiliency Plan was written to improve preparedness by reducing vulnerabilities to future drought events.

8

Impact: Increased growing season length and greater variability in temperature and precipitation stress critically important natural resources.

Response: The Platte Basin Timelapse project (PBT) uses time lapse photography and multimedia storytelling to document life across the Platte River watershed.

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

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.

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 River[36]—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 rates[42] 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

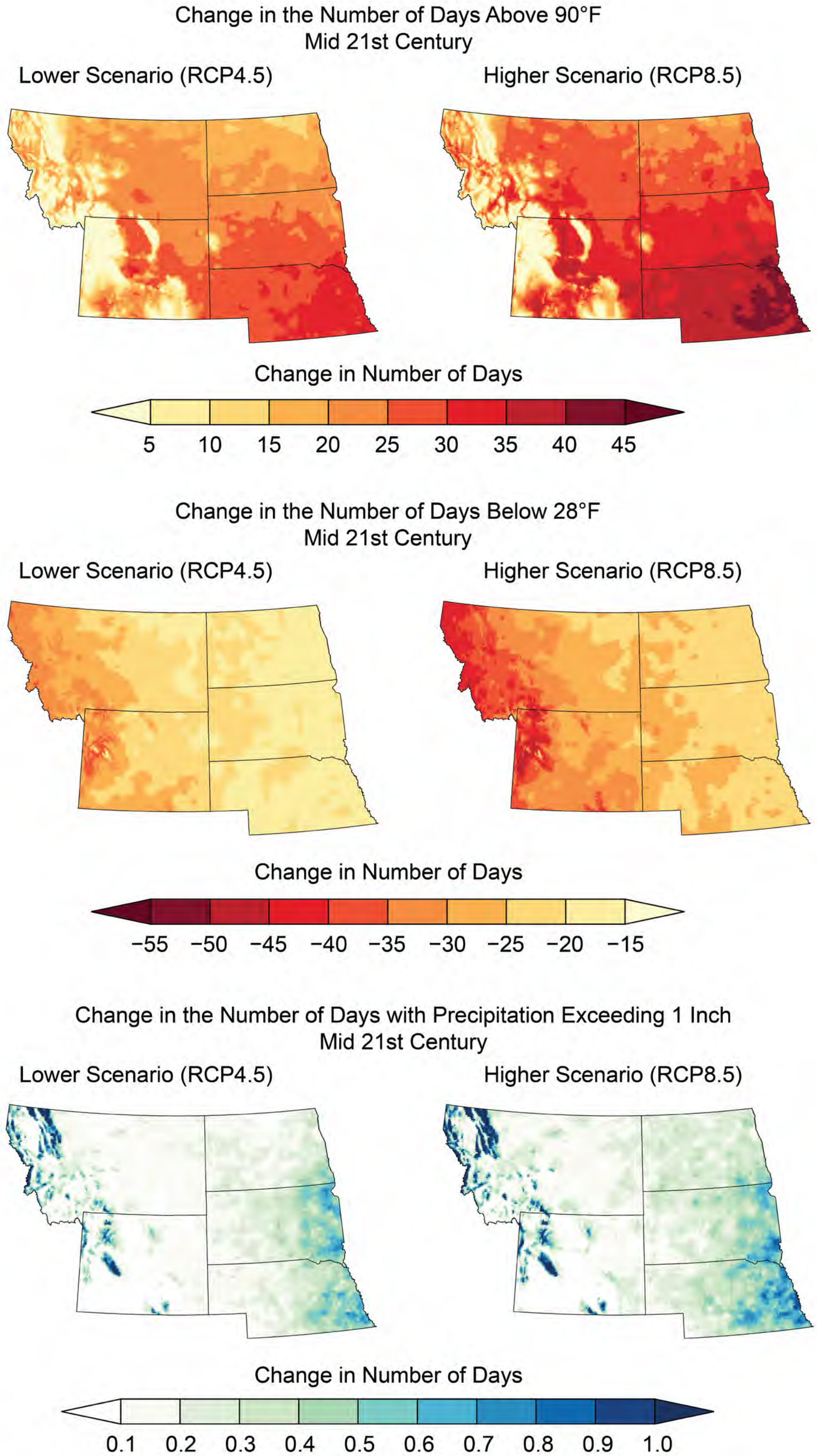


Figure 22.2: Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (middle) the annual number of cool days (days with minimum temperatures below 28°F, an indicator of damaging frost), 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.

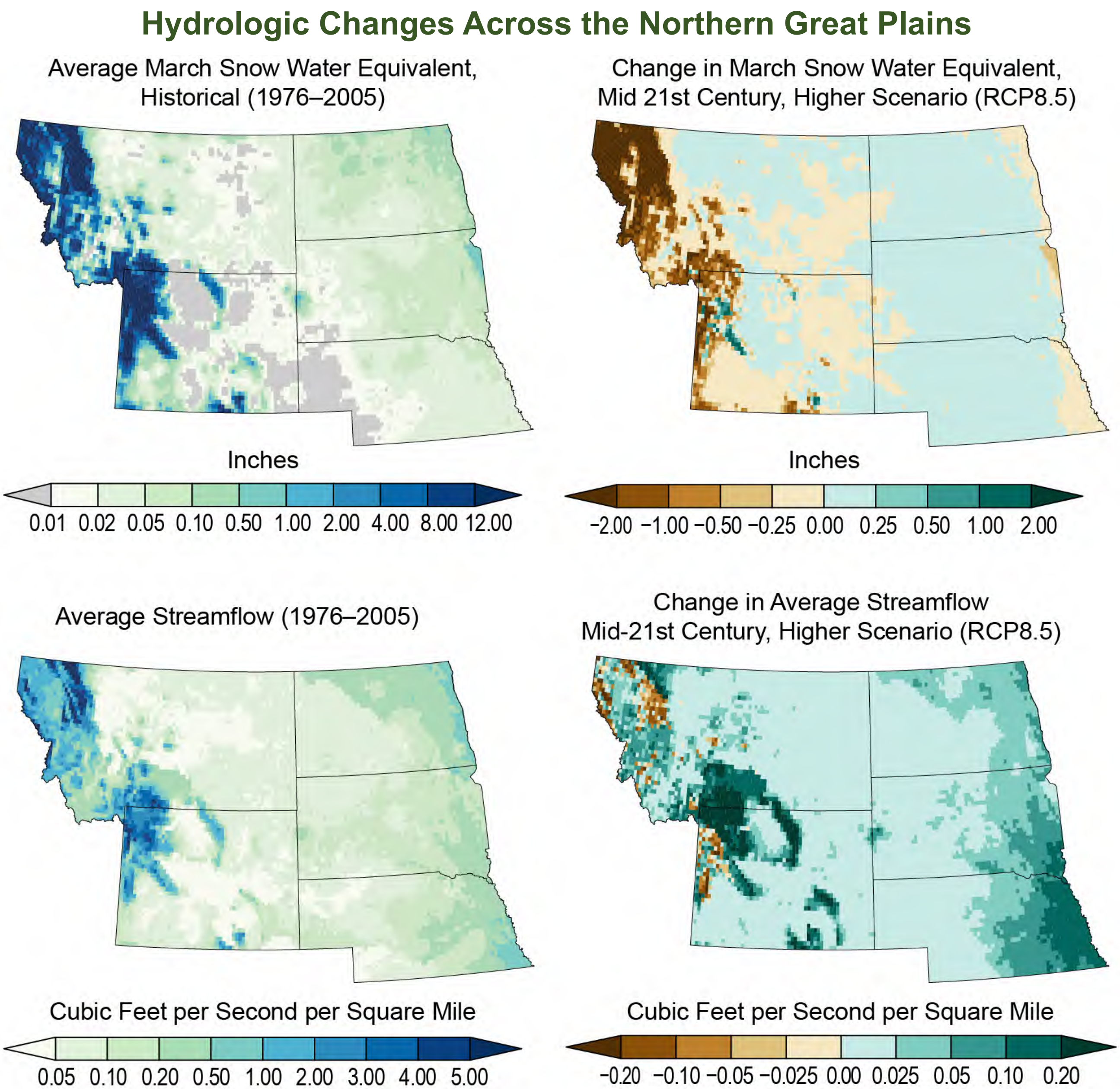


Figure 22.3 These maps show historical (left; 1976–2005) and projected changes (right; 2036-2065) under a higher scenario (RCP8.5) in average snowpack (top row) and annual streamflow (bottom row). Snowpack is measured in terms of snow water equivalent, or SWE—the depth in inches of the amount of water 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 (CO_2) 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 CO_2 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 crops[6] and forages[7,8] due to increasing temperatures, some of which will be offset by increasing CO_2;

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., Hotaling et al. 2017[78]) and ecosystem functions of riparian areas (areas along the banks of rivers and streams; e.g., Tonkin et al. 2018[79]), 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 families[102] 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 northwestward 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

	Changes in Area (thousands of acres)		
State	**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

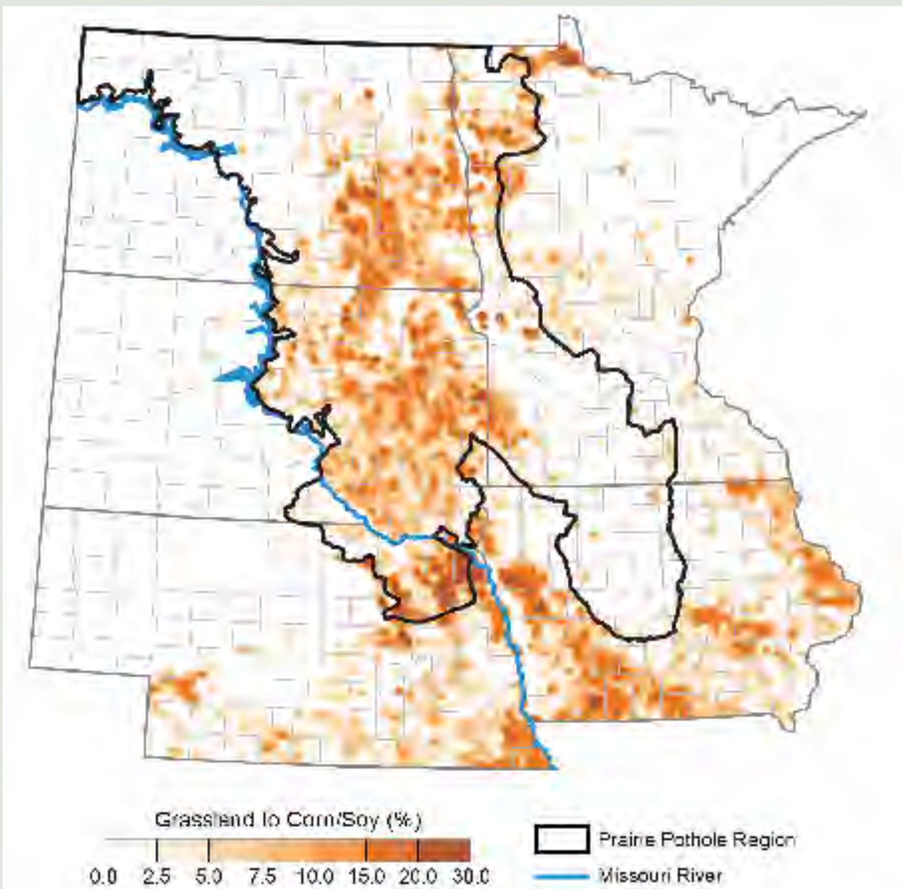


Figure 22.4: The figure shows the loss of grassland to corn/soy between 2006 and 2011 in the eastern states of the Northern Great Plains (Nebraska, South Dakota, and North Dakota), expressed as a percentage of 2006 grassland acres. Outlined in black is the boundary of the U.S. portion of the Prairie 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. CO_2 and methane are released during the production, transportation, and refining of petroleum. Coal mining also releases methane. CO_2 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

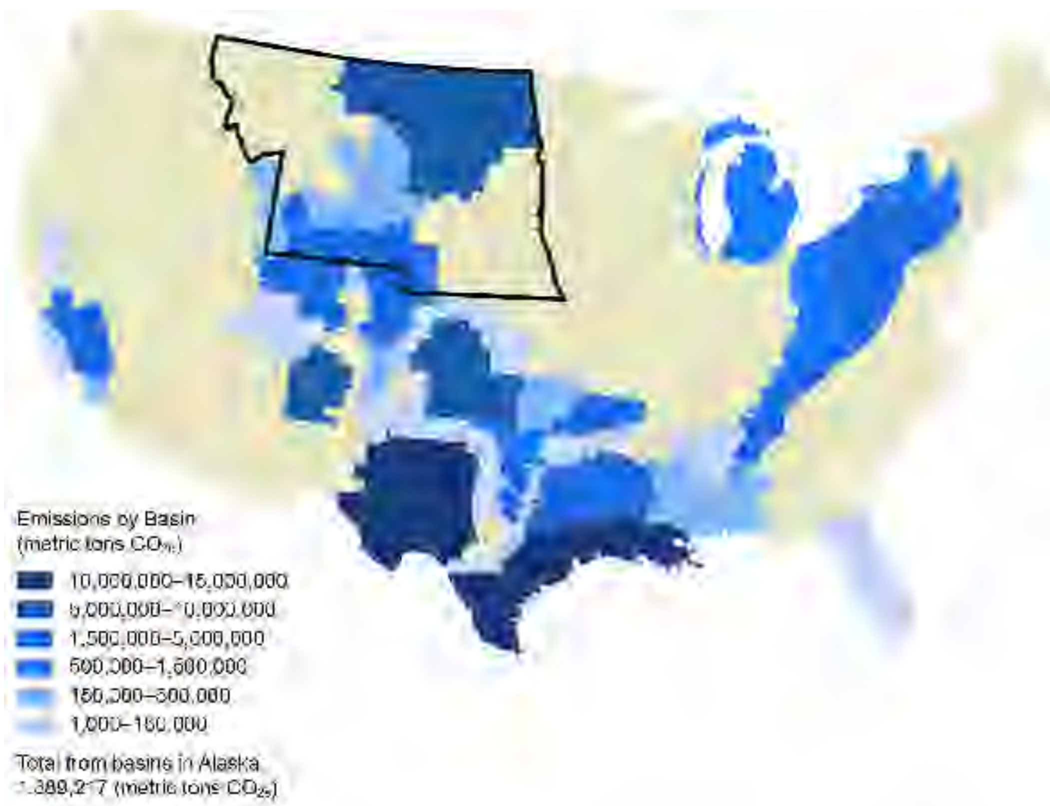


Figure 22.6: Greenhouse gas emissions (shown here in metric tons of carbon dioxide equivalent, or CO_{2e}, per geologic basin) from petroleum and natural gas production facilities in the Northern Great Plains are among the highest in the United States. The data used to produce this map are from EPA's 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

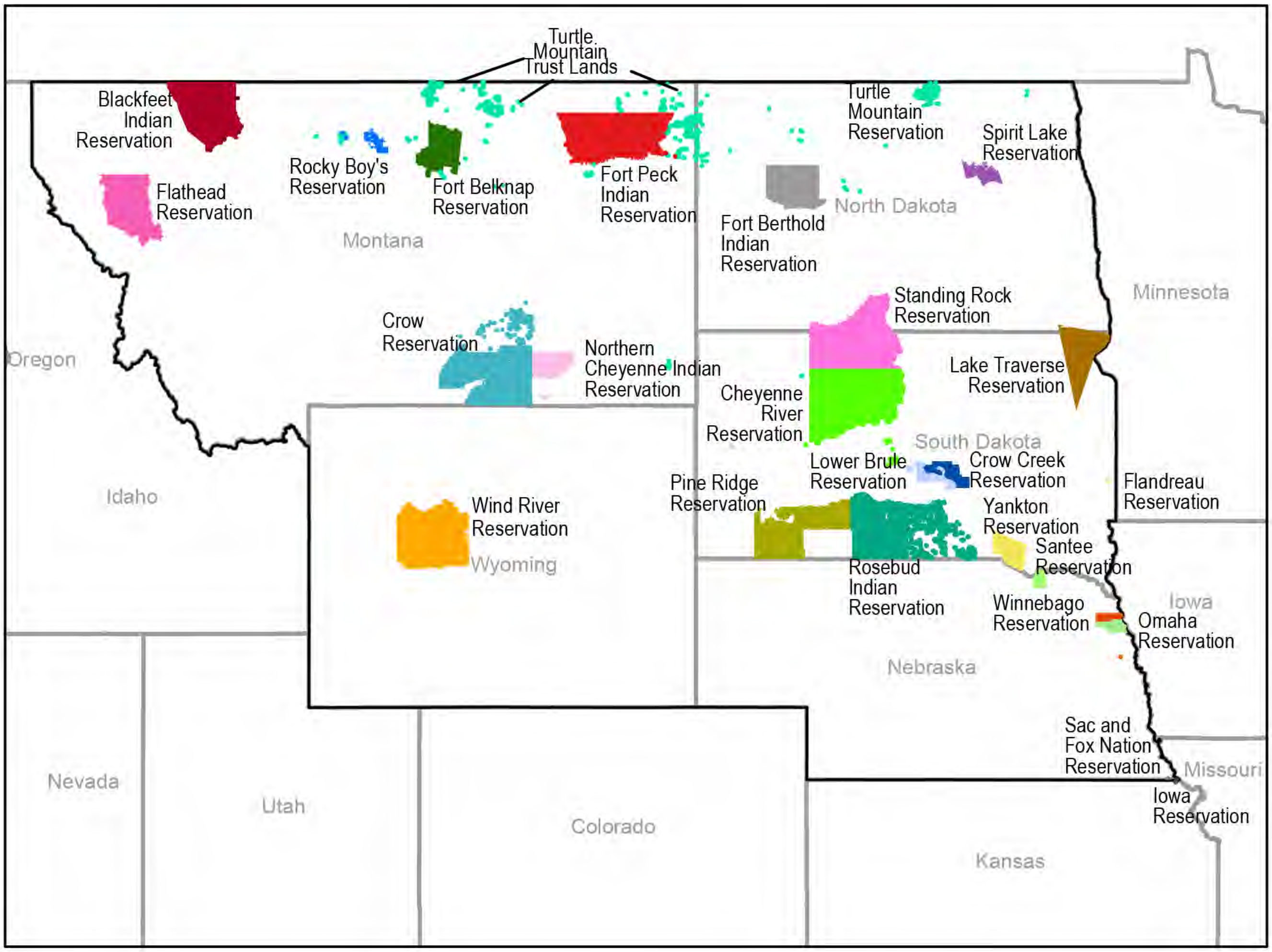


Figure 22.7: The map outlines reservation and off-reservation tribal lands in the Northern Great Plains, which shows where the 27 federally recognized tribes have a significant portion of lands throughout the region. Information on Indigenous peoples' climate projects within the Northern Great Plains 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 Bighorn 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

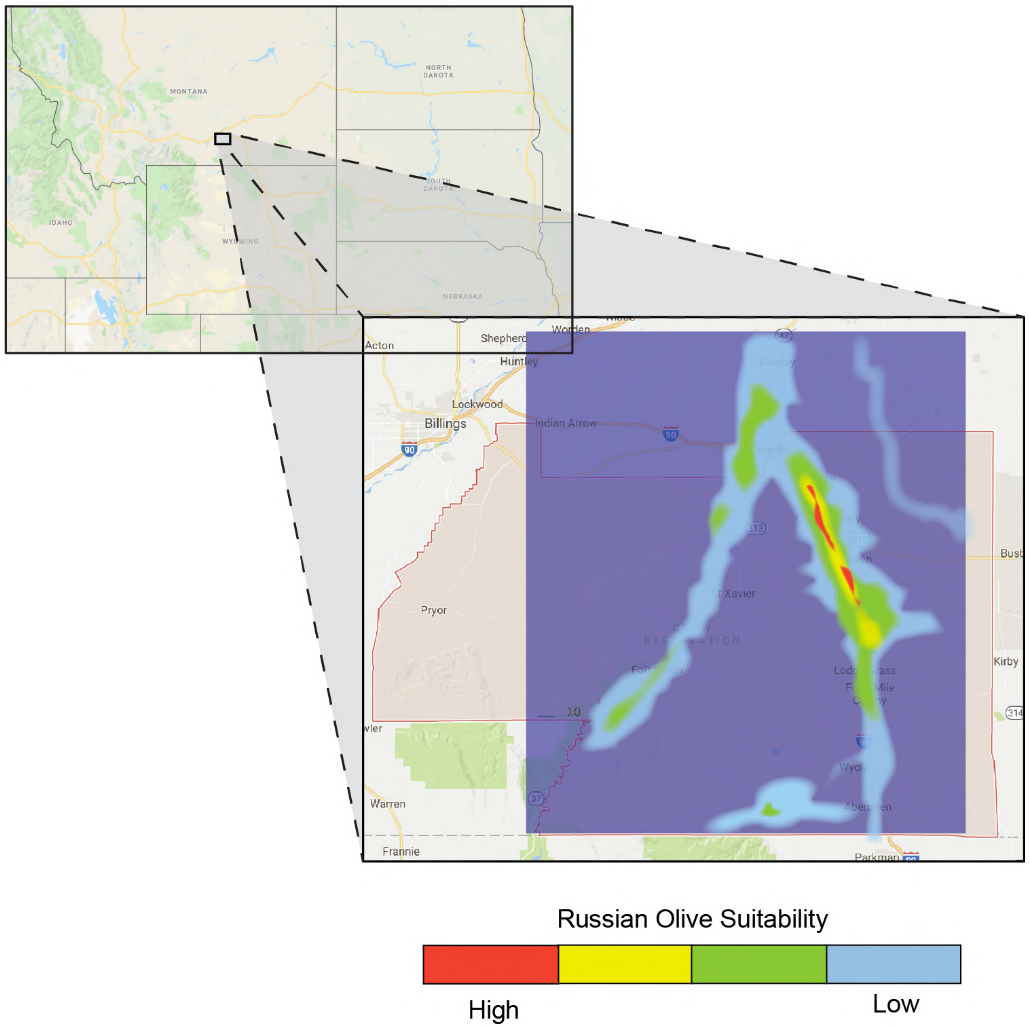


Figure 22.8: The map shows the projected expansion by 2021 of Russian olive habitat. Warmer colors indicate favorable habitat for future spread of Russian olive based on mapped presence points along the Little Bighorn and Bighorn Rivers within the Crow Indian Reservation in south central Montana. The 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]

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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 warming[39] 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 (CO_2) 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 year[35] 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 CO_2 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. 2006[83]). Region-inclusive studies are available (e.g., Wobus et al. 2017[11]) 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 Pakota, 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 (O_3) 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 O_3 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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Exhibit 4

26 Alaska

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26 Alaska

Anchorage, Alaska

Key Message 1

Marine Ecosystems

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

Key Message 2

Terrestrial Processes

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

Key Message 3

Human Health

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

Key Message 4

Indigenous Peoples

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

Key Message 5

Economic Costs

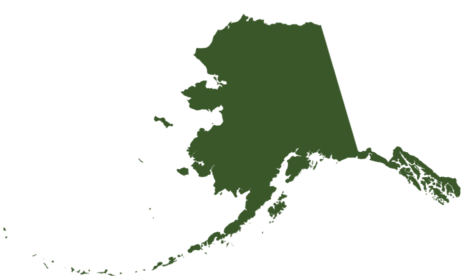
Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska. It is also reducing heating costs throughout the state. These effects are very likely to grow with continued warming. Timely repair and maintenance of infrastructure can reduce the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

Key Message 6

Adaptation

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

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 (CO_2) emissions and negatively affects organisms. Climate change will likely affect management actions and economic drivers, including fisheries, in complex ways. The use of multiple alternative models to appropriately characterize uncertainty in future fisheries biomass trajectories and harvests could help manage these challenges. As temperature and precipitation increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost is expected to continue, with associated impacts to infrastructure, river and stream discharge, water quality, and fish and wildlife habitat.

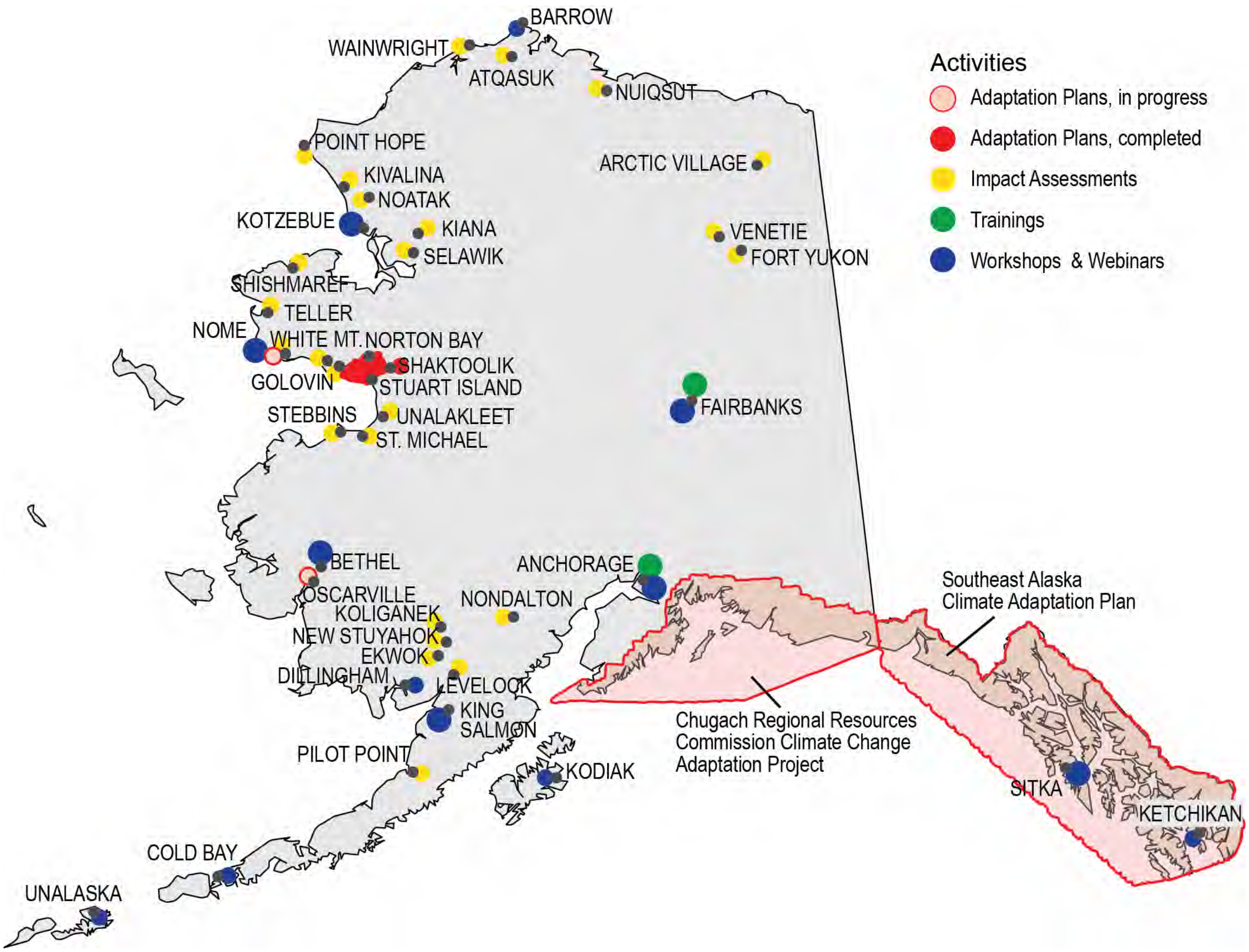
Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat in the future and in some cases requiring entire communities or portions of communities to relocate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

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

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

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

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 2017[8]).*

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

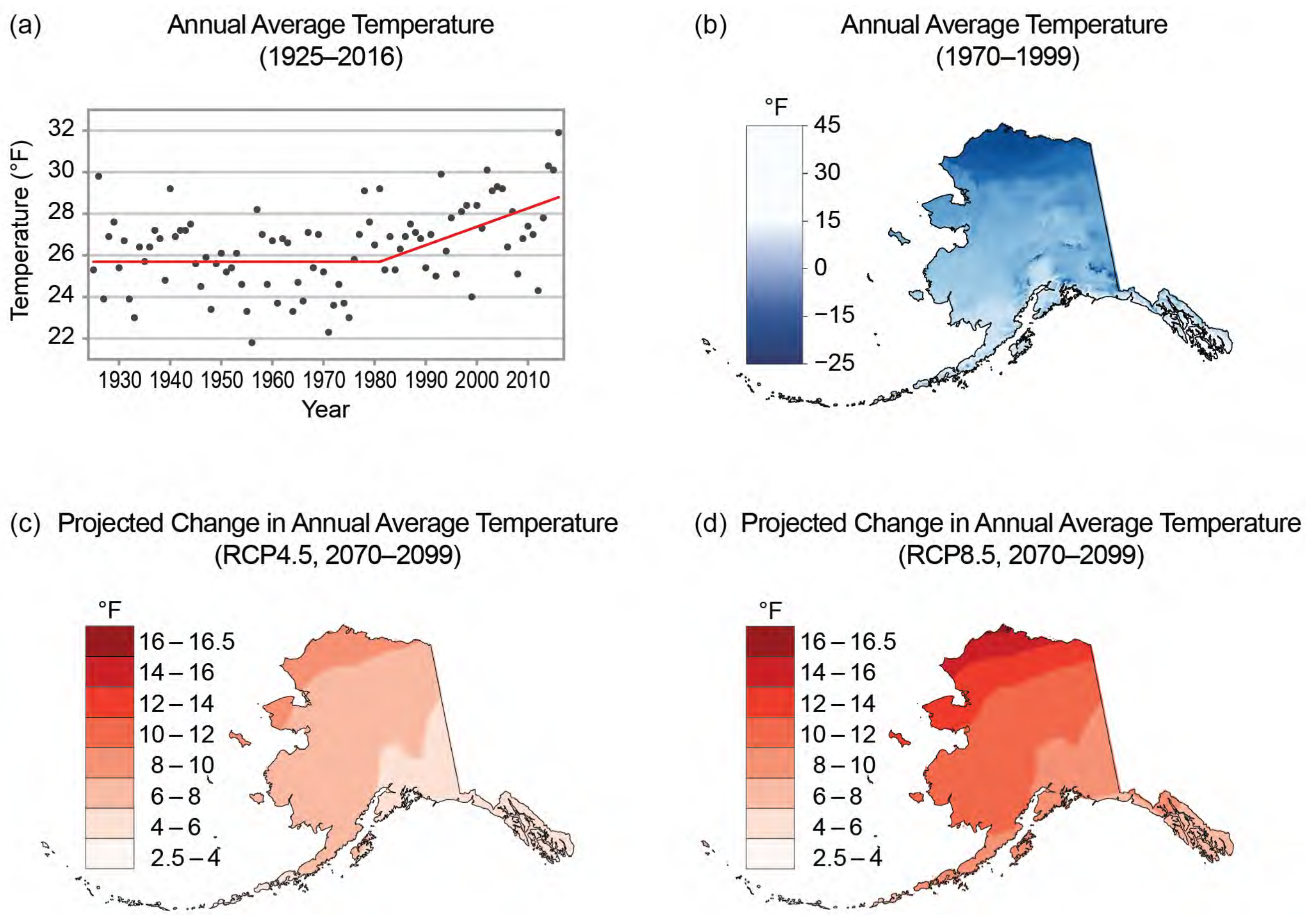


Figure 26.1: (a) The graph shows Alaska statewide annual average temperatures for 1925–2016. The record shows no clear change from 1925 to 1976 due to high variability, but from 1976–2016 a clear trend of +0.7°F per decade is evident. (b) The map shows 1970–1999 annual average temperature. Alaska has 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 models[43] 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 walruses[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 Walruses

Polar bears and walruses 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 walruses 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 walruses 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) Walruses 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 (CO_2) 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 CO_2.[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-latitudinal ecosystems with fewer species and shorter food chains.[67,68]

Projected Changes in Arctic Ocean Acidity

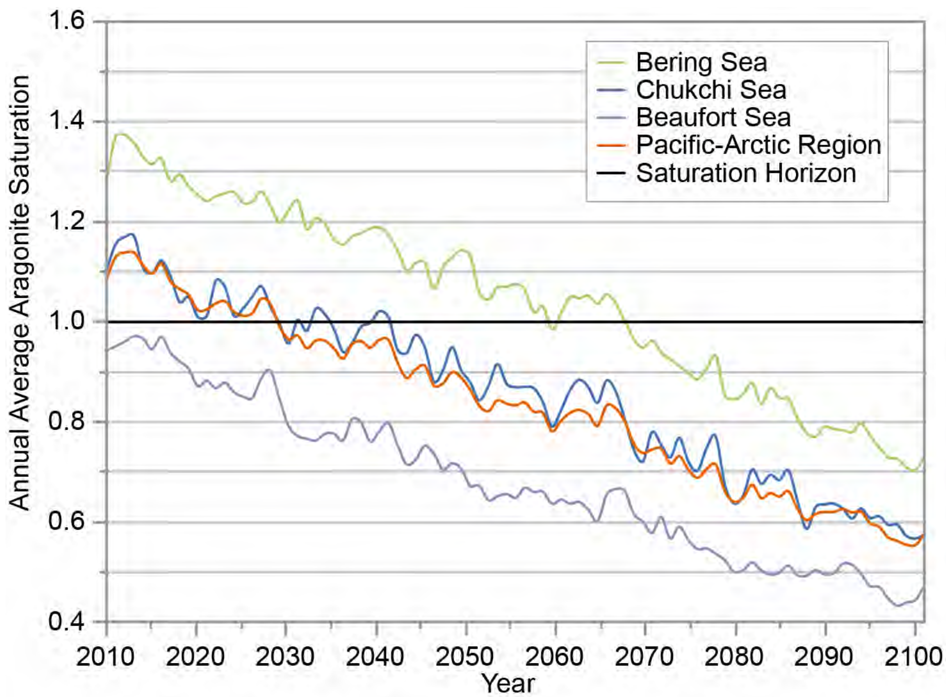


Figure 26.3: The time series shows the projected decline in the annual average aragonite saturation (one of the consequences of increased ocean acidity, or lower pH) for the Bering Sea, Chukchi Sea, Beaufort Sea, and for the entire Pacific-Arctic region under the higher scenario (RCP8.5). Aragonite saturation 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

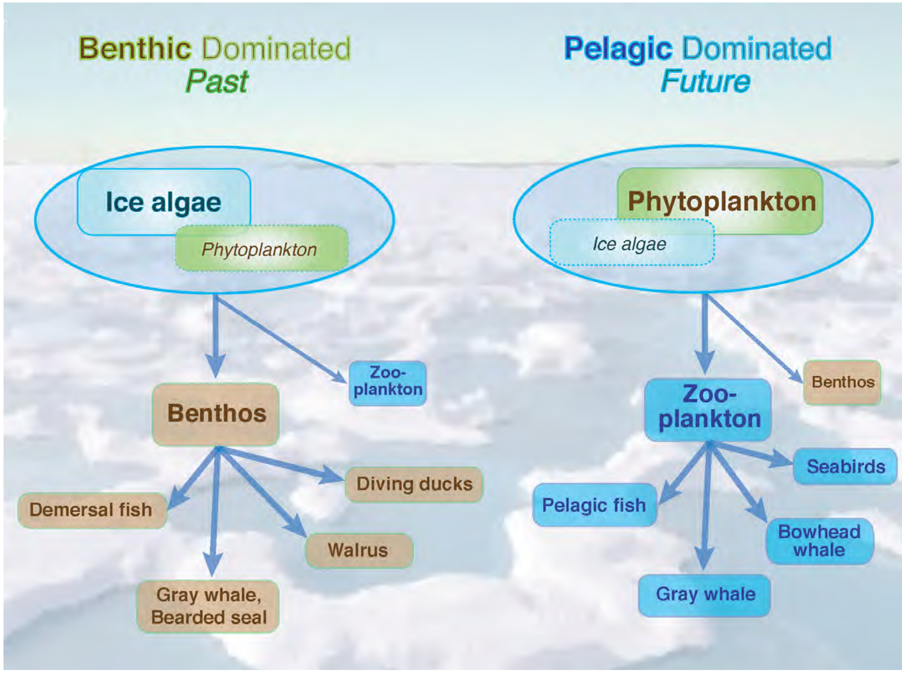


Figure 26.4: As sea ice thins and retreats earlier in the season, it is anticipated that food webs under the ice will switch from a benthic-dominated (lower in the water to seafloor) to a pelagic-dominated (middle to higher in the water) marine ecosystem. Source: Moore and Stabeno 2015.[78]

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 modeling[107] 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 Assessment[109] 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

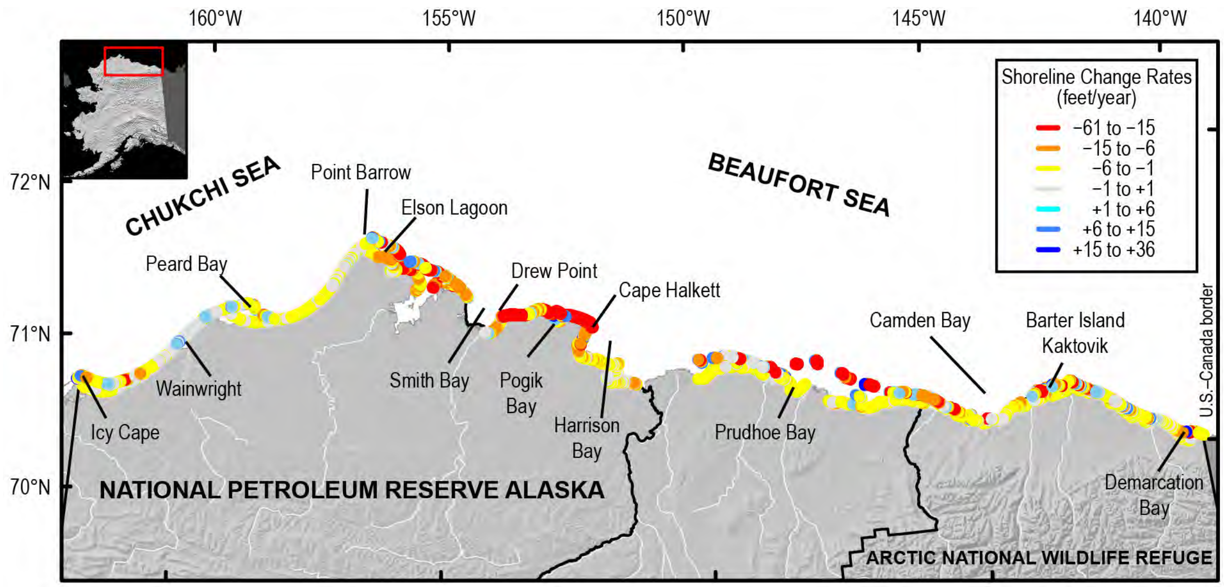


Figure 26.5: The map is of the north coast of Alaska and shows color-coded shoreline erosion rates, which can lead to the loss of habitat, cultural resources, and infrastructure. Source: adapted from Gibbs and Richmond 2015.[19]

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 Alaska[143] 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 Fairbanks[161] 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 seals[194] 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 environment[112] 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 scenario[11] (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 relocated[123] 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 activity[103] 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 discharge[227] 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 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.

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 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 Utqiaġvik (formerly known as Barrow; Figure 26.8).[238]

Energy Needed for Heating Decreases Across Much of Alaska

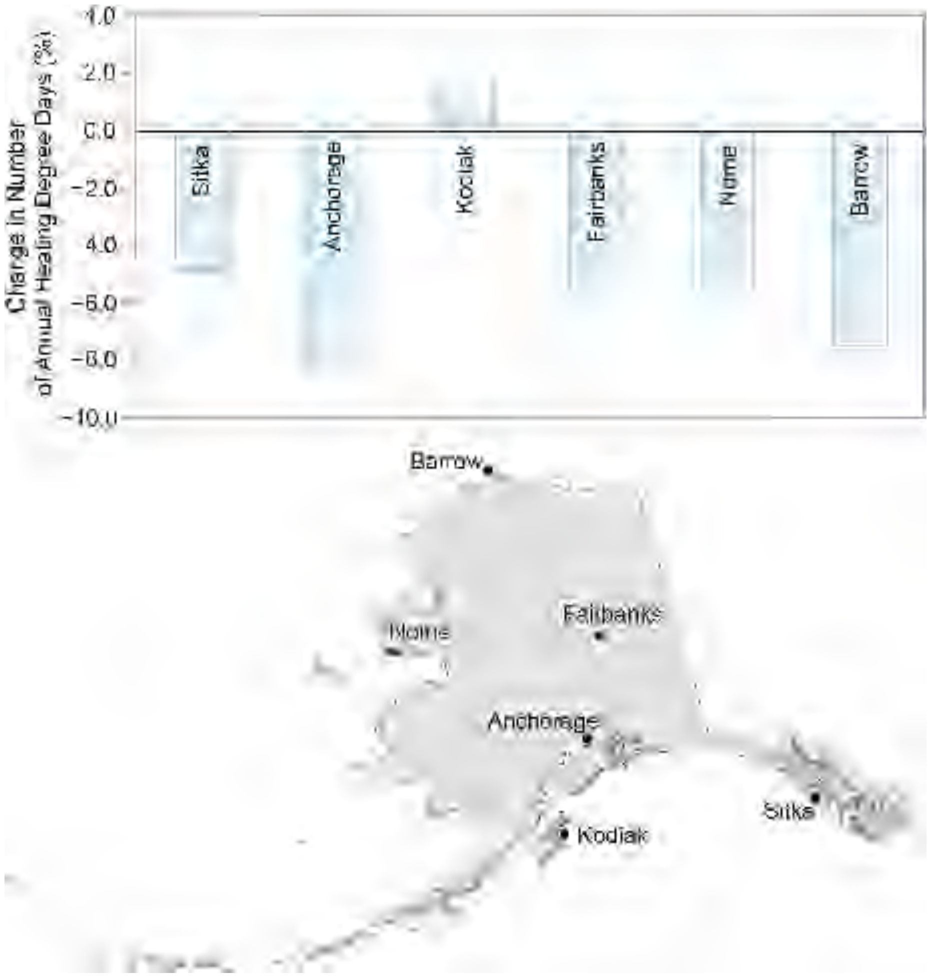


Figure 26.8: The chart shows the percentage change in annual heating degree days for the period 2000–2015 (as compared to 1950–1979) for six Alaska communities. Every 1% decline in heating degree days could potentially yield $10 million of annual savings in heating costs. Sources: University of Alaska 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 effects[242] 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 change [249] and ocean acidification.[250]

Key elements of successful adaptation in Alaska include coordinated consideration of both environmental and social conditions[134] 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

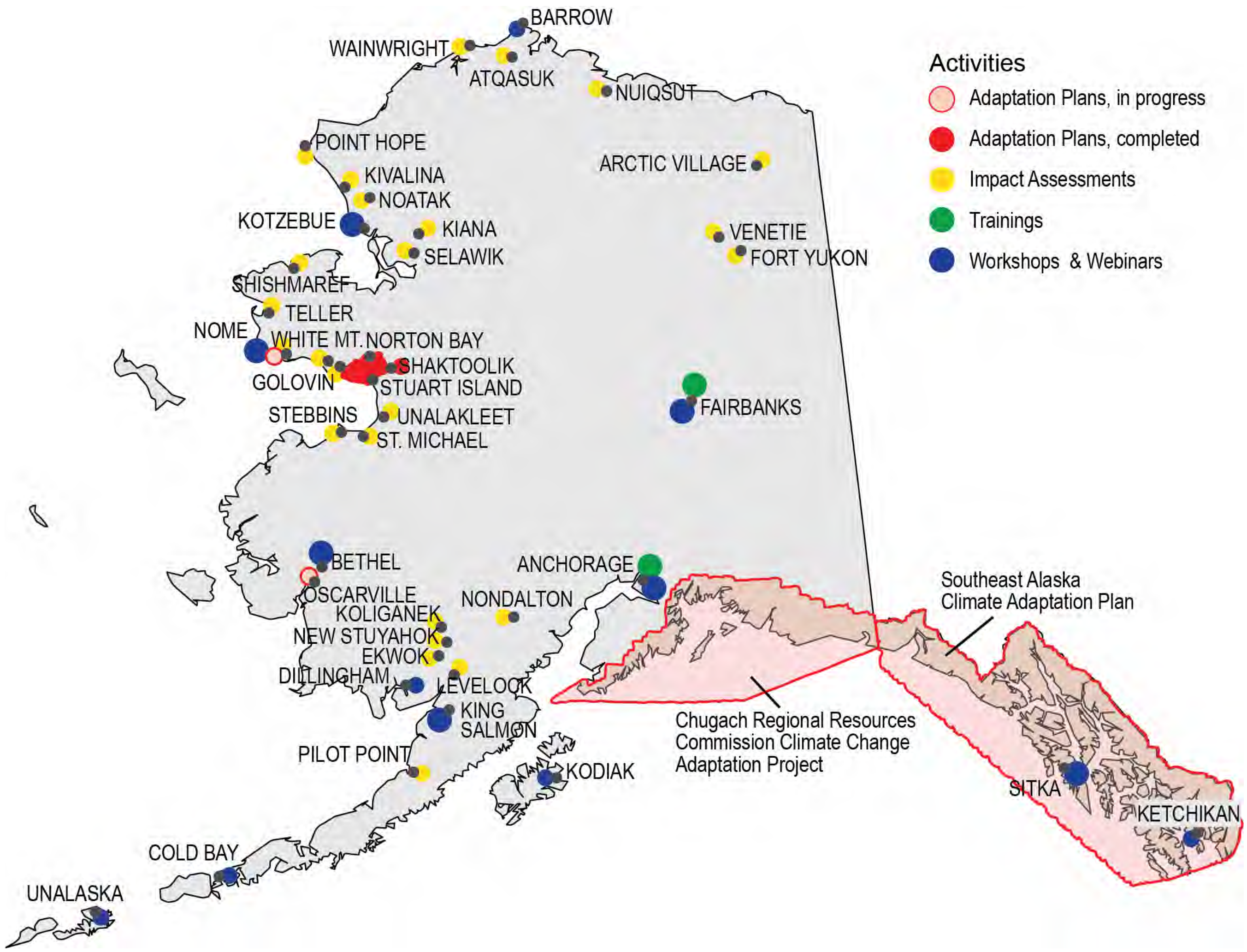


Figure 26.9: The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, 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 charts[276] 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]

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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 records[280] 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 CO_2 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 acidification[18] and expanding deeper into the Arctic Basin[57] 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 ground[105] 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 shorelines[19] 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 area[137] 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 Utqiaġvik (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 change[249] 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 though 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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Exhibit 5

25 Southwest

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25 Southwest

Low water levels in Lake Mead

Key Message 1

Water Resources

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

Key Message 2

Ecosystems and Ecosystem Services

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

Key Message 3

The Coast

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

Key Message 4

Indigenous Peoples

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

Key Message 5

Energy

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

Key Message 6

Food

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

Key Message 7

Human Health

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

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.

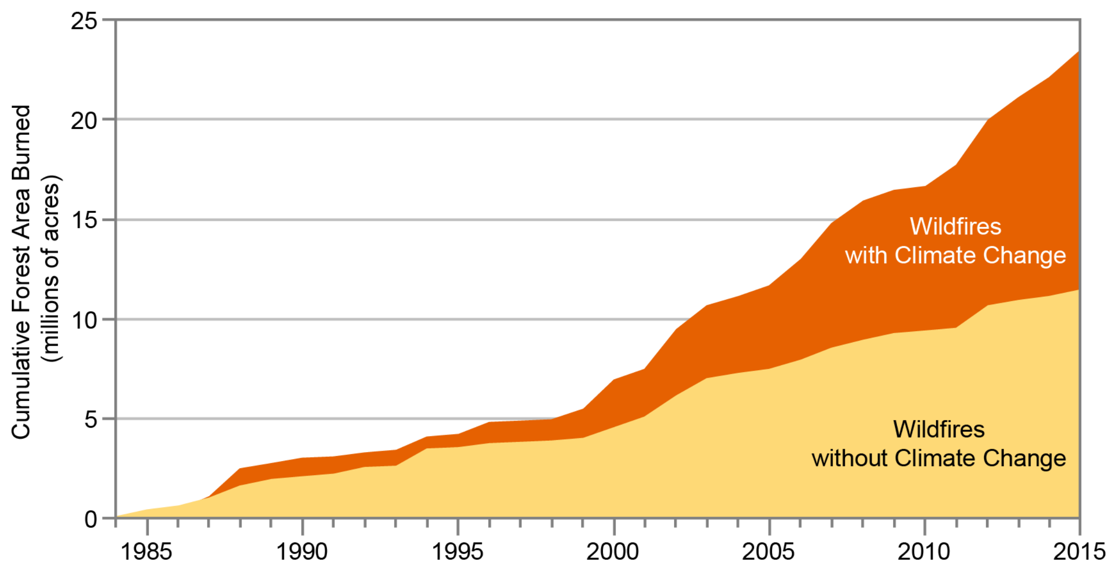
At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016. Climate change caused most of this rise by melting of land ice and thermal expansion of ocean water. Local governments on the California coast are using projections of sea level rise to develop plans to 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.

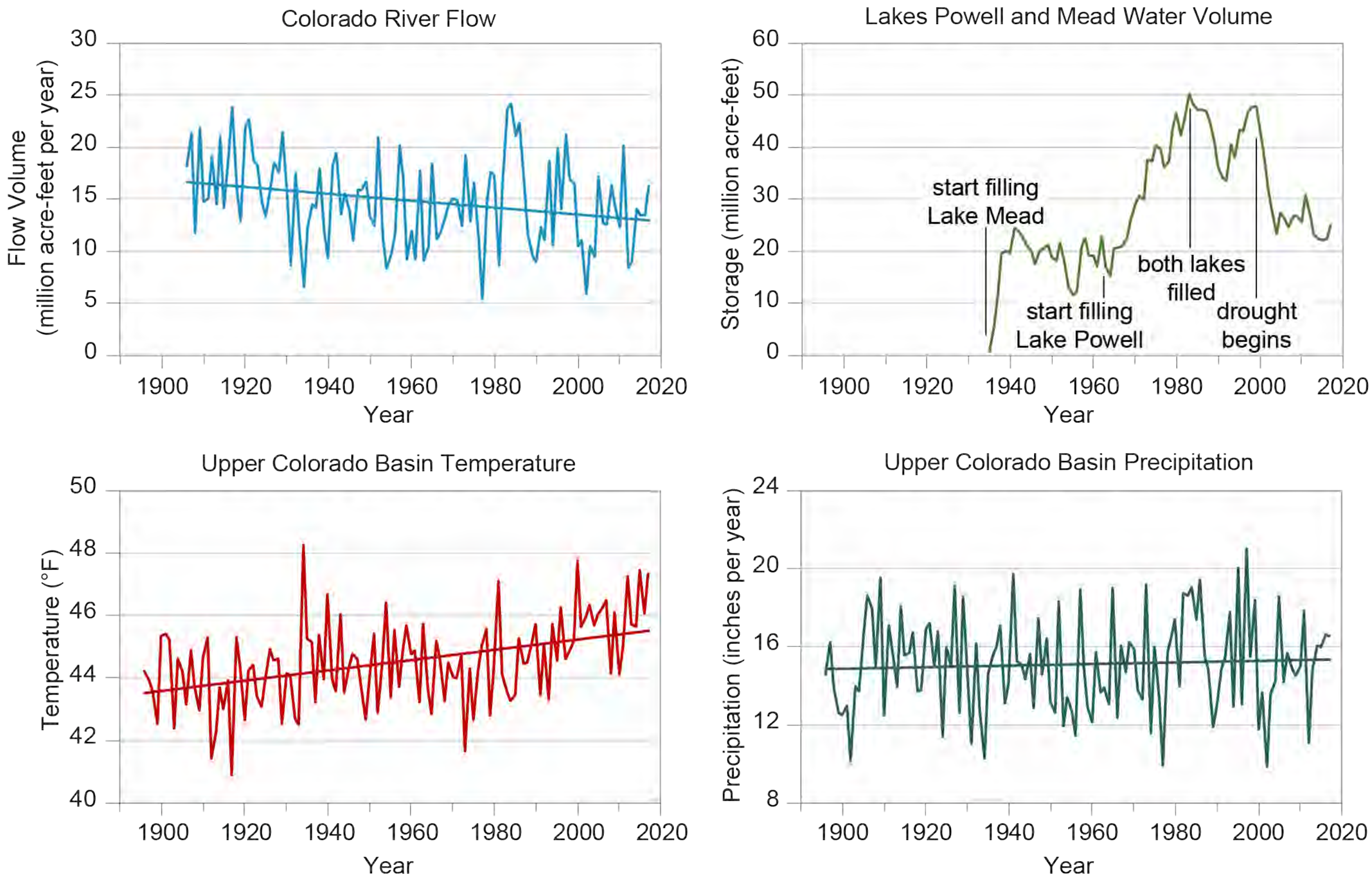
The severe drought in California, intensified by climate change, reduced hydroelectric generation two-thirds from 2011 to 2015. The efficiency of all water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency 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 shifts[213] 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 nuts[2] and most of the wine grapes, strawberries, and lettuce[17] 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, California[19] 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 1880[21] 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

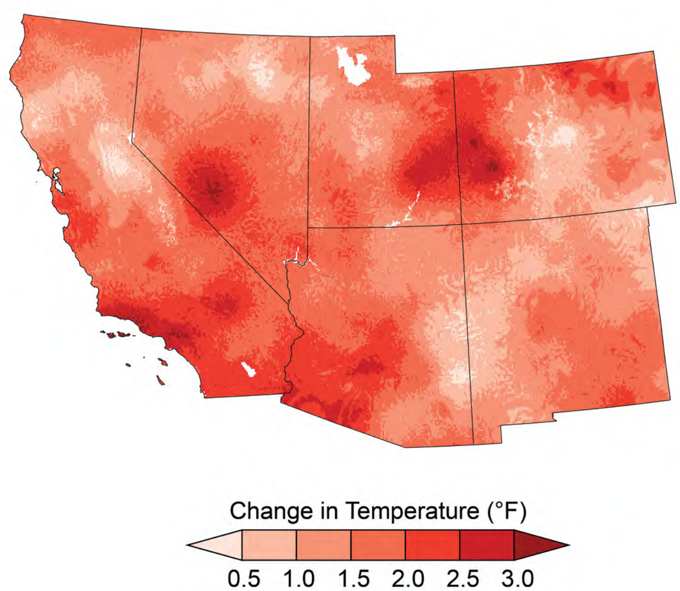


Figure 25.1: Temperatures increased across almost all of the Southwest region from 1901 to 2016, with the greatest increases in southern California and western Colorado.[23] This map shows the difference between 1986–2016 average temperature and 1901–1960 average temperature.[23] Source: adapted from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

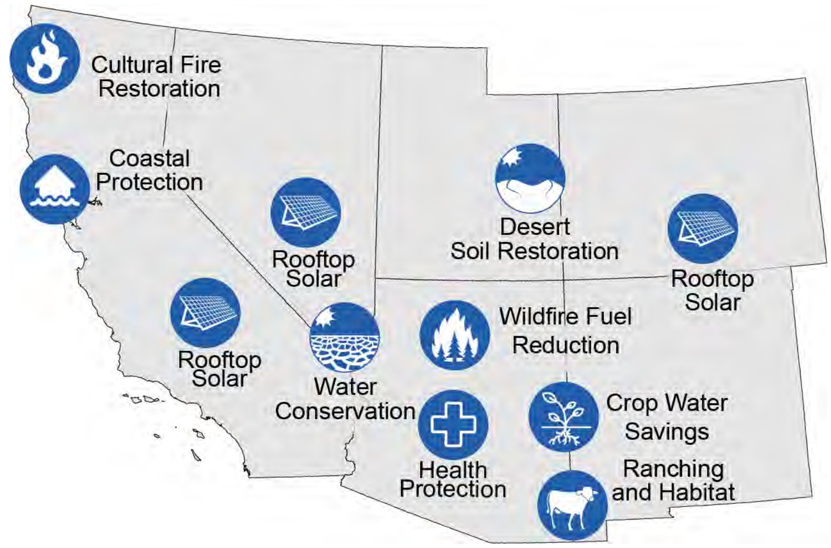


Figure 25.2: These examples illustrate actions that people, communities, and governments are taking in response to past impacts of climate change and future vulnerabilities. **Coastal protection**: In response to sea level rise and storm surge in San Francisco Bay, federal, state, and local agencies, 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 efficiency[60] 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 problems[127] and populations vulnerable to flooding,[127,128] projected increases in heavy precipitation[88] 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:

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

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]

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

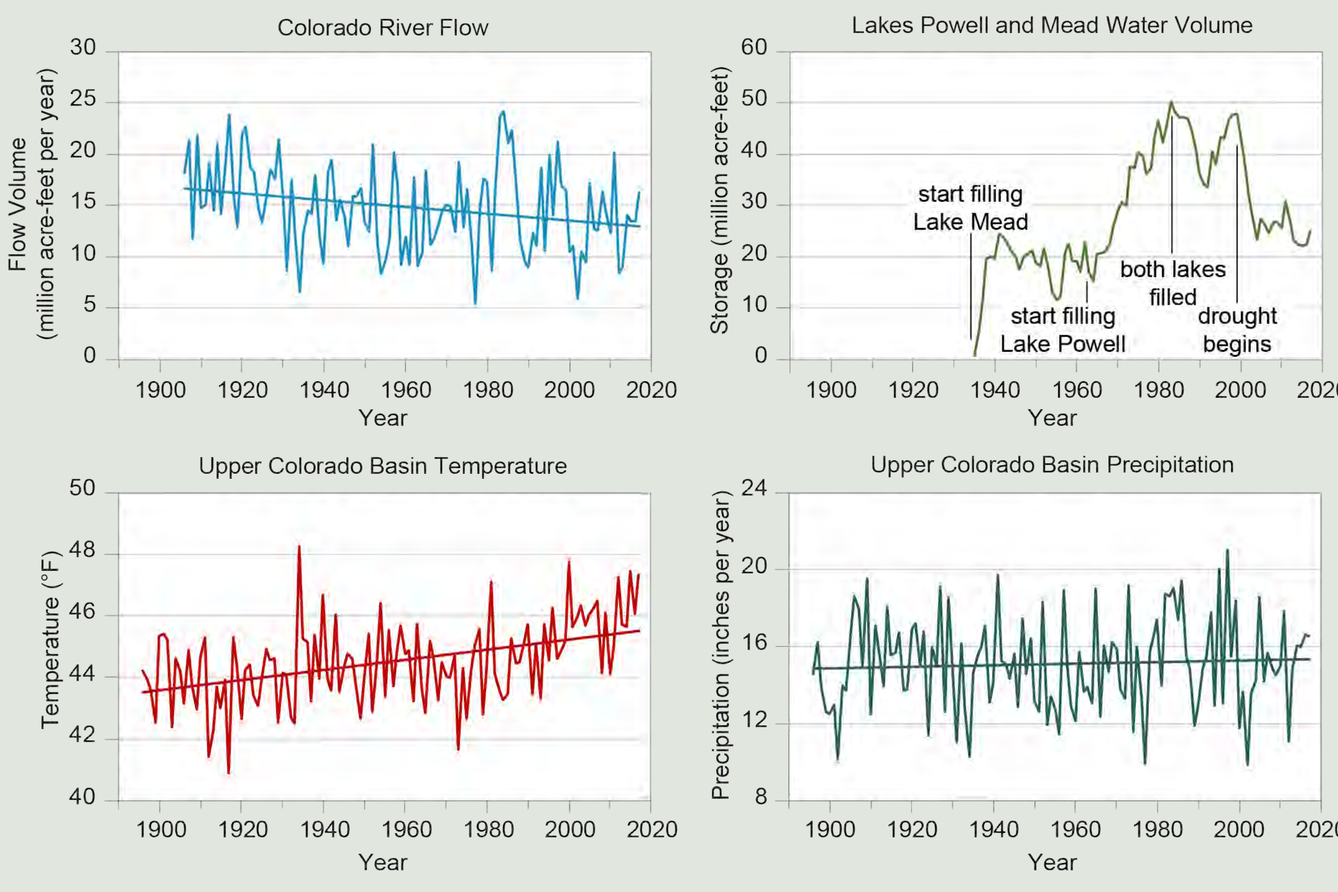


Figure 25.3: Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (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]

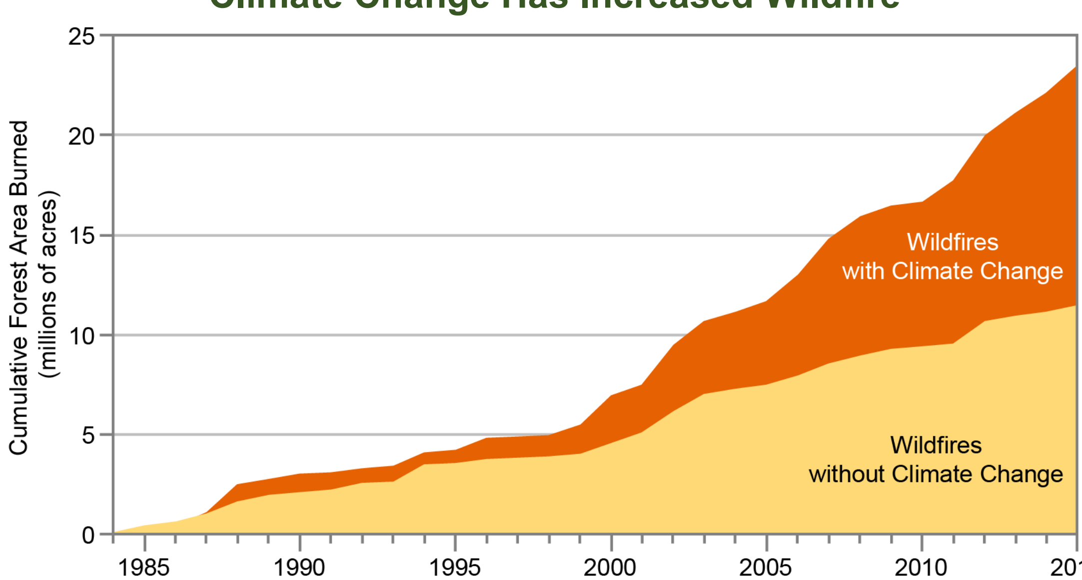


Figure 25.4: The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. Source: adapted from Abatzoglou 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 California[175] 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 B1[174]), 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 plants[194] 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 Islands[214] 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 2100[244] 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 Francisco[250] 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).

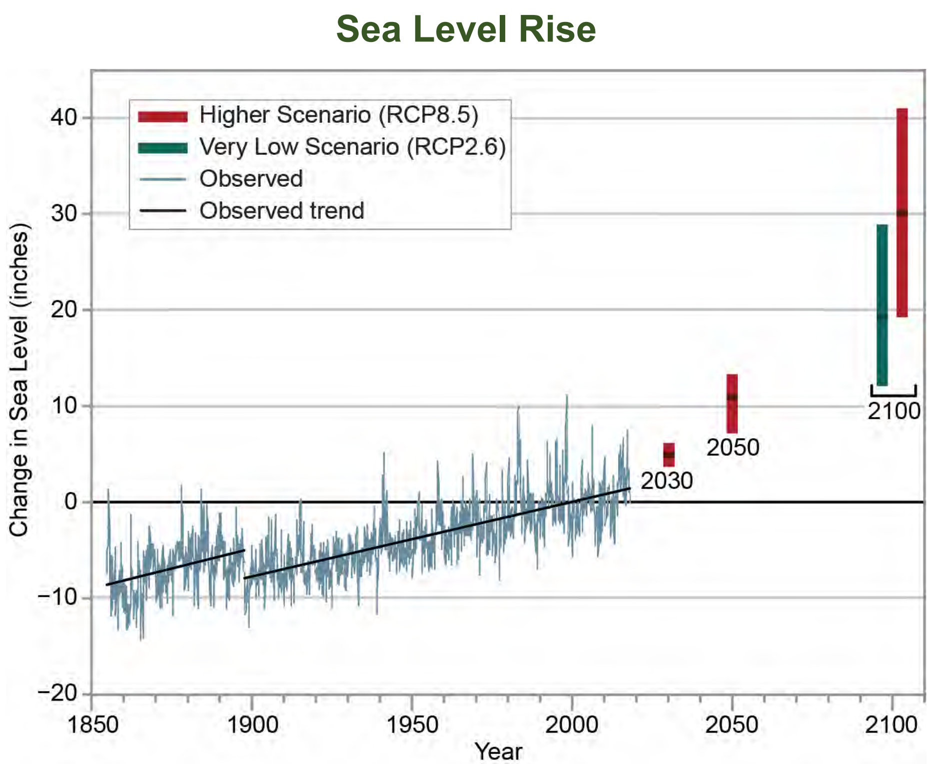


Figure 25.5: Sea level rise increases risks to infrastructure. At the Golden Gate Bridge in San Francisco, California, the tidal gauge with the longest time series in the Western Hemisphere shows that sea level has risen nearly 9 inches (22 cm) since 1854 (blue line).[236,295] In 1897, the tidal gauge 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.

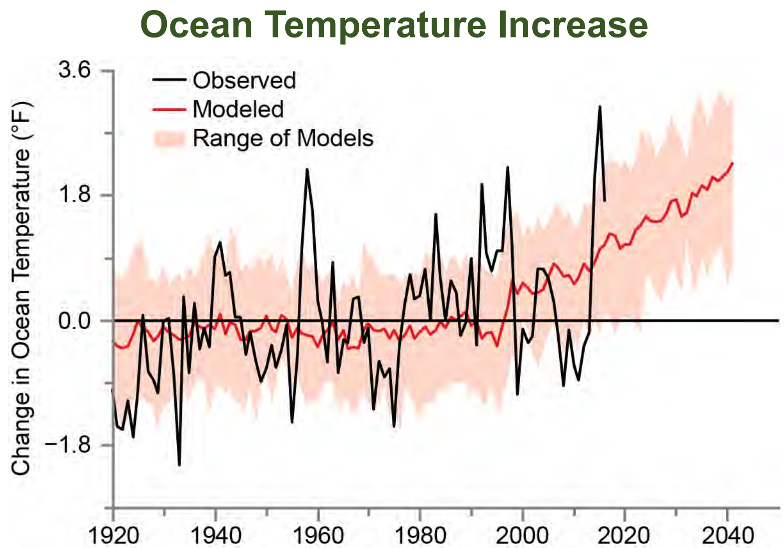


Figure 25.6 Ocean warming increases risks to fisheries and shellfish. The graph shows observed ocean temperatures of the California Current from measurements (black line); modeled temperatures, extended into the future under the higher scenario (RCP8.5; red line); and the range of 10% to 90% of the 28 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 2030[285] 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 intergenerational 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 Maidu[328] 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 year[105] 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

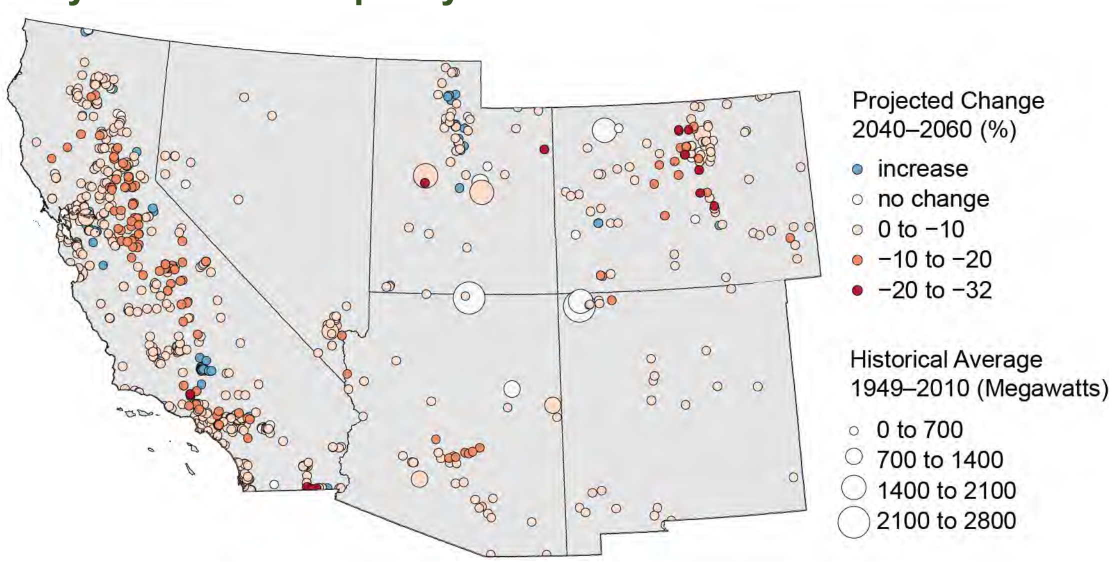


Figure 25.8: Under a higher emissions scenario (SRES A2[174]), heat-induced reduction of energy efficiency and reduced water flows would reduce summer energy generation capacity across the Southwest region. These projected reductions would increase risks of electricity shortages. The map shows projected 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 risk[13] and higher aridity[70] 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 corn[372] 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

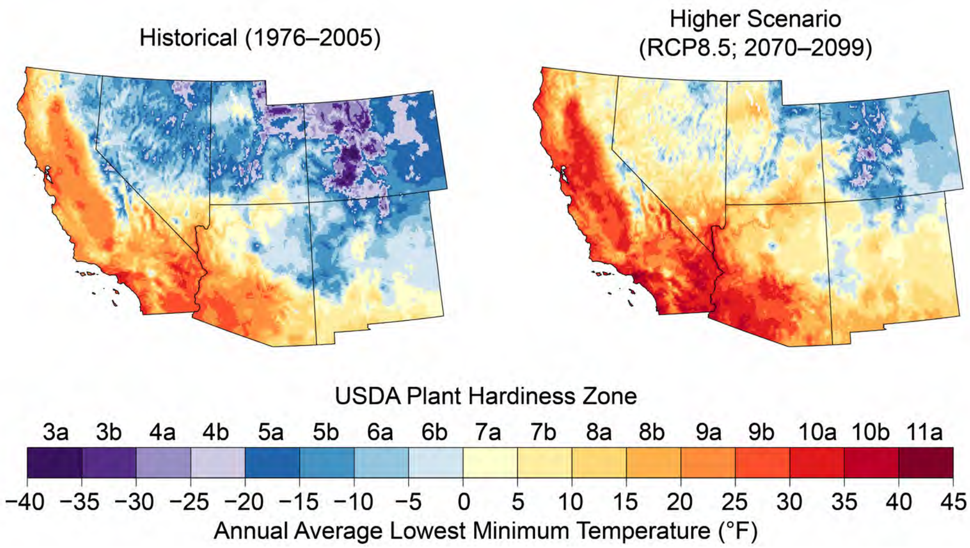


Figure 25.9: The U.S. Department of Agriculture plant hardiness zones indicate the cold temperature requirements of crops. Increases in temperature under the higher scenario (RCP8.5), would shift these zones northward and upslope, from the period 1976—2005 (left, modeled historical) compared to projections 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 foods[298] 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 nights[23] 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

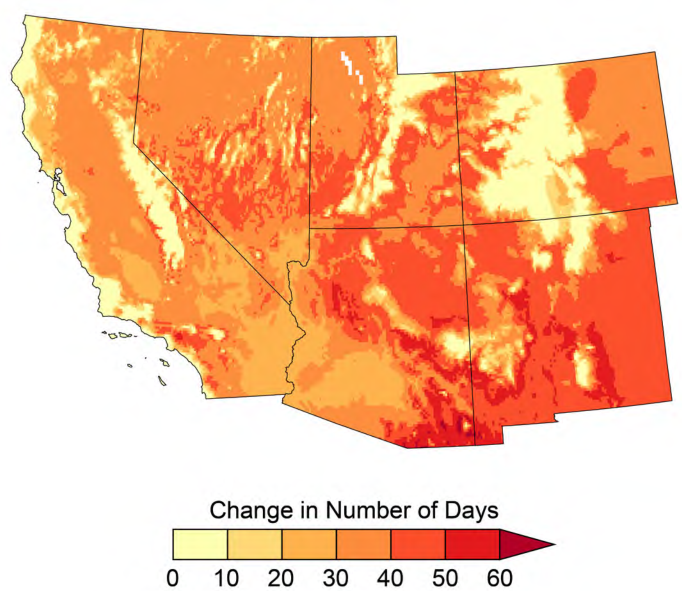


Figure 25.10: Under the higher scenario (RCP8.5), extreme heat would increase across the Southwest, shown here as the increase in the average number of days per year when the temperature exceeds 90°F (32°C) by the period 2036–2065, compared to the period 1976–2005.[23] Heat waves increase the exposure of people to heat stroke and other illnesses that could cause death.[30] Source: adapted from Vose et al. 2017.[23]

Elevated levels of CO_2 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 preventable[460] 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

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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 2007[146] 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 futures[152] 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 ± 0.4°F (1.1 ± 0.2°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 projections[242] 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. 2016[493]), 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 generation[335] 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 corn[372] 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 costs[371]—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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