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15: BIOGEOCHEMICAL CYCLES

SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting text summarize extensive evidence documented in two technical input reports submitted to the NCA: 1) a foundational report supported by the Departments of Energy and Agriculture: *Biogeochemical Cycles and Biogenic Greenhouse Gases from North American Terrestrial Ecosystems: A Technical Input Report for the National Climate Assessment*,[30] and 2) an external report: *The Role of Nitrogen in Climate Change and the Impacts of Nitrogen-Climate Interactions on Terrestrial and Aquatic Ecosystems, Agriculture, and Human Health in the United States: A Technical Report Submitted to the U.S. National Climate Assessment*.[4] The latter report was supported by the International Nitrogen Initiative, a National Science Foundation grant, and the David and Lucille Packard Foundation.

Author meetings and workshops were held regularly for the foundational report,[30] including a workshop at the 2011 Soil Science Society of America meeting. A workshop held in July 2011 at the USGS John Wesley Powell Center for Analysis and Synthesis in Fort Collins, CO, focused on climate-nitrogen actions and was summarized in the second primary source.[4] An additional 15 technical input reports on various topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The entire author team for this chapter conducted its deliberations by teleconference from April to June 2012, with three major meetings resulting in an outline and a set of key messages. The team came to expert consensus on all of the key messages based on their reading of the technical inputs, other published literature, and professional judgment. Several original key messages were later combined into a broader set of statements while retaining most of the original content of the chapter. Major revisions to the key messages, chapter, and traceable accounts were approved by authors; further minor revisions were consistent with the messages intended by the authors.

Key message #1 Traceable Account

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,31] In particular, one report[4] focused on changes in the nitrogen cycle and was comprehensive. Original literature was consulted for changes in other biogeochemical cycles. The foundational report[30] updated several aspects of our understanding of the carbon balance in the United States.

Publications have shown that human activities have altered biogeochemical cycles. A seminal paper comparing increases in the global fluxes of carbon (C), nitrogen (N), sulfur (S), and phosphorous (P) was published in 2000[73] and was recently updated.[3] Changes observed in the nitrogen cycle[1,17,18] show anthropogenic sources to be far greater than natural ones.[14,36,47] For phosphorus, the effect of added phosphorus on plants and microbes is well understood.[19,46,47] Extensive research shows that increases in CO_2 are the strongest human impact forcing climate change, mainly because the concentration of CO_2 is so much greater than that of other greenhouse gases.[5,7,73]

New information and remaining uncertainties

The sources of C, N, and P are from well-documented processes, such as fossil fuel burning and fertilizer production and application. The flux from some processes is well known, while others have significant remaining uncertainties.

Some new work has synthesized the assessment of global and national CO_2 emissions[7] and categorized the major CO_2 sources and sinks.[4,30] Annual updates of CO_2 emissions and sink inventories are done by EPA (for example, EPA 2013[8]).

Advances in the knowledge of the nitrogen cycle have quantified that human-caused reactive nitrogen inputs are now at least five times greater than natural inputs.[4,13,14]

Assessment of confidence based on evidence

High confidence. Evidence for human inputs of C, N, and P come from academic, government, and industry sources. The data show substantial agreement.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

The likelihood of continued dominance of CO_2 over other greenhouse gases as a driver of global climate change is also judged to be **high**, because its concentration is an order of magnitude higher and its rate of change is well known.

Key message #2 Traceable Account

In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO2 and other greenhouse gases.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,30] The "Estimating the U.S. Carbon Sink" section relies on multiple sources of data that are described therein.

Numerous studies of the North American and U.S. carbon sink have been published in reports and the scientific literature. Estimates of the percentage of fossil fuel CO_2 emissions that are captured by forest, cropland, and other lands vary from a low of 7% to a high of about 24%, when the carbon storage is estimated from carbon inventories.[7,22,36] The forest sink has persisted in the U.S. as forests that were previously cut have regrown. Further studies show that carbon uptake can be increased to some extent by a fertilization effect with reactive nitrogen[44,45] and phosphorus,[46,47,48] both nutrients that can limit the rate of photosynthesis. The carbon sink due to nitrogen fertilization is projected to lessen in the future as controls on nitrogen emissions come into play.[28]

While carbon uptake by ecosystems has a net cooling effect, trace gases emitted by ecosystems have a warming effect that can offset the cooling effect of the carbon sink.[26] The most important of these gases are methane and nitrous oxide (N_2O), the concentrations of which are projected to rise.[25,26,33,37,38]

New information and remaining uncertainties

The carbon sink estimates have very wide margins of error. The percent of U.S. CO_2 emissions that are stored in ecosystems depends on which years are used for emissions and whether inventories, ecosystem process models, atmospheric inverse models, or some combination of these techniques are used to estimate the sink size (see "Estimating the U.S. Carbon Sink"). The inventories are continually updated (for example, EPA 2013[8]), but there is a lack of congruence on which of the three techniques is most reliable. A recent paper that uses atmospheric inverse modeling suggests that the global land and ocean carbon sinks are stable or increasing.[69]

While known to be significant, continental-scale fluxes and sources of the greenhouse gases N_2O and CH_4 are based on limited data and are potentially subject to revision. Recent syntheses[28] evaluate the dynamics of these two important gases and project future changes. Uncertainties remain high.

Assessment of confidence based on evidence

We have **very high** confidence that the value of the forest carbon sink lies within the range given, 7% to 24% (with a best estimate of 16%) of annual U.S. greenhouse gas emissions. There is wide acceptance that forests and soils store carbon in North America, and that they will continue to do so into the near future. The exact value of the sink strength is very poorly constrained, however, and knowledge of the projected future sink is low. As forests age, their capacity to store carbon in living biomass will necessarily decrease,[10] but if other, unknown sinks are dominant, ecosystems may continue to be a carbon sink.

We have **high** confidence that the combination of ecosystem carbon storage of human-caused greenhouse gas emissions and potential warming from other trace gases emitted by ecosystems will ultimately result in a net warming effect. This is based primarily on one recent synthesis,[28] which provides ranges for multiple factors and describes the effects of propagating uncertainties. However, the exact amount of warming or cooling produced by various gases is not yet well known, because of the interactions of multiple factors.

Key message #3 Traceable Account

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Description of evidence base

The author team evaluated technical input reports (17) on biogeochemical cycles, including the two primary sources.[4,30]

The climate–biogeochemical cycle link has been demonstrated through numerous studies on the effects of reactive nitrogen and phosphorus on forest carbon uptake and storage, and decomposition of organic matter;[44,53] temperature effects on ecosystem productivity;[54] and sensitivity of natural methane emissions to climate variation.[55]

Where the nitrogen and phosphorus cycles are concerned, a number of publications have reported effects of excess loading on ecosystem processes[60,61] and have projected these effects to worsen.[61,62] Additionally, studies have reported the potential for future climate change and increasing nitrogen and phosphorus loadings to have an additive effect and the need for remediation.[18,61] The literature suggests that co-benefits are possible from addressing the environmental concerns of both nutrient loading and climate change.[4,31,64,65,66]

New information and remaining uncertainties

Scientists are still investigating the impact of nitrogen deposition on carbon uptake and of sulfur and nitrogen aerosols on radiative forcing.

Recent work has shown that more than just climate change aspects can benefit from addressing multiple environmental concerns (air/water quality, biodiversity, food security, human health, and so on)

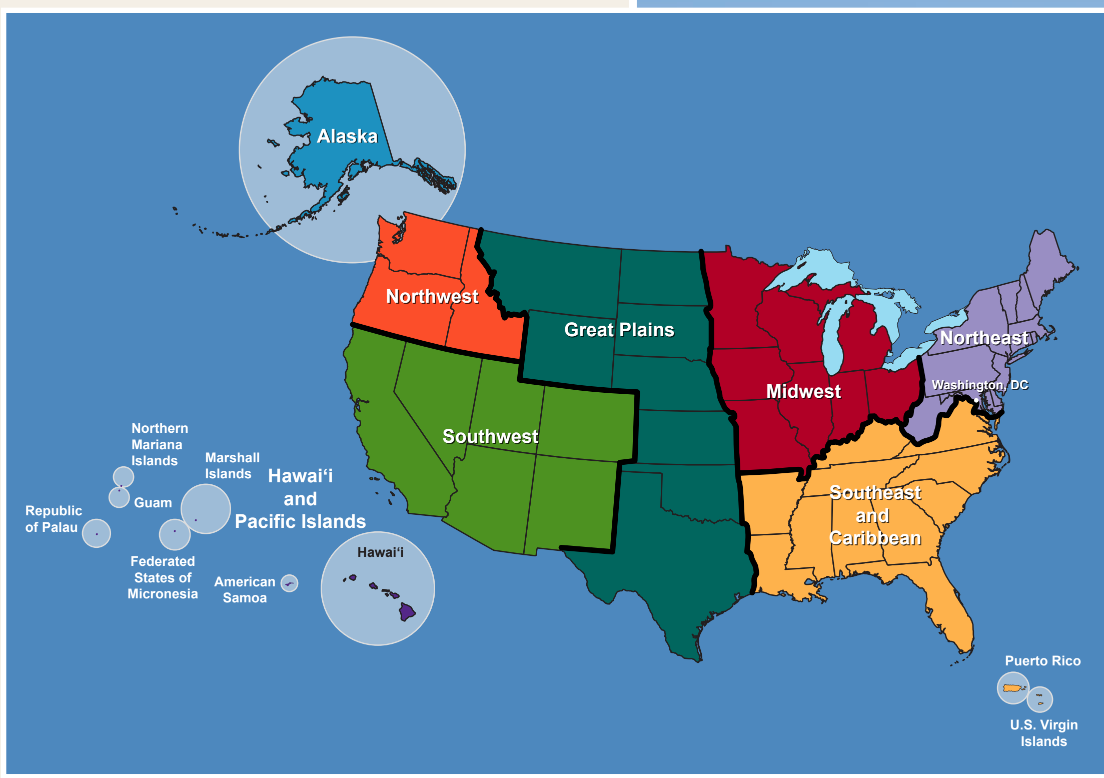
Assessment of confidence based on evidence

High. We have a **high** degree of confidence that climate change will affect biogeochemical cycles through its effects on ecosystem structure and function (species composition and productivity). Similarly, there is **high** confidence that altered biogeochemical cycles will affect climate change, as for example in the increased rates of carbon storage in forests and soils that often accompany excess nitrogen deposition.

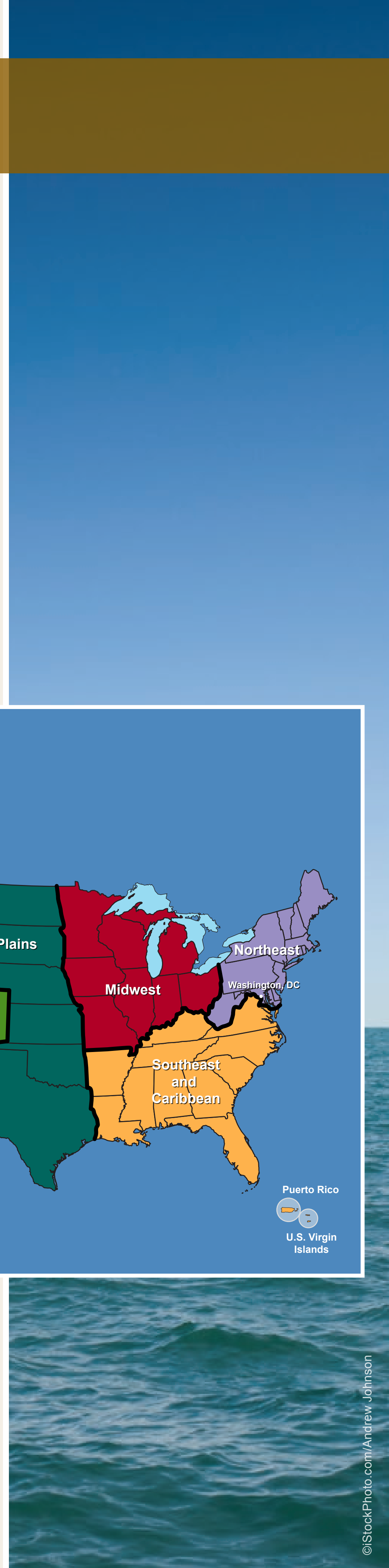
REGIONS

From the Rocky Mountains to the Shenandoah Valley, the Great Lakes to the Gulf of Mexico, our country's landscapes and communities vary dramatically. But amidst our geographical and economic diversity, we share many common attributes and challenges. One common challenge facing every U.S. region is a new and dynamic set of realities resulting from our changing climate.

The evidence can be found in every region, and impacts are visible in every state. Some of the most dramatic changes are in Alaska, where average temperatures have increased more than twice as fast as the rest of the country. The rapid decline of Arctic sea ice cover in the last decade is reshaping that region. In the Southwest, a combination of increased temperatures and reductions in annual precipitation are already affecting forests and diminishing water supplies. Meanwhile, that region's population continues to grow at double-digit rates, increasing the stress on water supplies. In various regions, evidence of climate change is apparent in ecosystem changes, such as species moving northward, increases in invasive species and insect outbreaks, and changes in the length of the growing season. In many cities, impacts to the urban environment are closely linked to the changing climate, with increased flooding, greater incidence of heat waves, and diminished air quality. Along most of our coastlines, increasing sea levels and associated threats to coastal areas and infrastructure are becoming a common experience.



For all U.S. regions, warming in the future is projected to be very large compared to historical variations. Precipitation patterns will be altered as well, with some regions becoming drier and some wetter. The exact location of some of these future changes is not easy to pinpoint, because the continental U.S. straddles a transition zone between projected drier conditions in the sub-tropics (south) and wetter conditions at higher latitudes (north). As a result, projected precipitation changes in the northernmost states (which will get wetter) and southernmost states (which will get drier) are more certain than those for the central areas of the country. The heaviest precipitation events are projected to increase everywhere, and by large amounts. Extended dry spells are also projected to increase in length.



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Regional differences in climate change impacts provide opportunities as well as challenges. A changing climate requires alterations in historical agricultural practices, which, if properly anticipated, can have some benefits. Warmer winters mean reductions in heating costs for those in the northern portions of the country. Well-designed adaptation and mitigation actions that take advantage of regional conditions can significantly enhance the nation's resilience in the face of multiple challenges, which include many factors in addition to climate change.

The regions defined in this report intentionally follow state lines (see Figure 1 and Table 1), but landscape features such as forests and mountain ranges do not follow these artificial boundaries. The array of distinct landscapes within each region required difficult choices of emphasis for the authors. The chapters that follow provide a summary of changes and impacts that are observed and anticipated in each of the eight regions of the United States, as well as on oceans and coasts.

For more information about the regional climate histories and projections[1] and sea level rise scenarios[2] developed for the National Climate Assessment, and used throughout this report, see Ch. 2: Our Changing Climate and Appendix 5: Scenarios and Model

Table 1: Composition of NCA Regions

Region	Composition
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia, District of Columbia,
Southeast and Caribbean	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, Puerto Rico, U.S. Virgin Islands
Midwest	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
Great Plains	Kansas, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, Wyoming
Northwest	Idaho, Oregon, Washington
Southwest	Arizona, California, Colorado, Nevada, New Mexico, Utah
Alaska	Alaska
Hawai'i and U.S. Pacific Islands	Hawai'i, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Republic of the Marshall Islands, Republic of Palau, Territory of American Samoa, Territory of Guam

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Climate Change Impacts in the United States

CHAPTER 16
NORTHEAST

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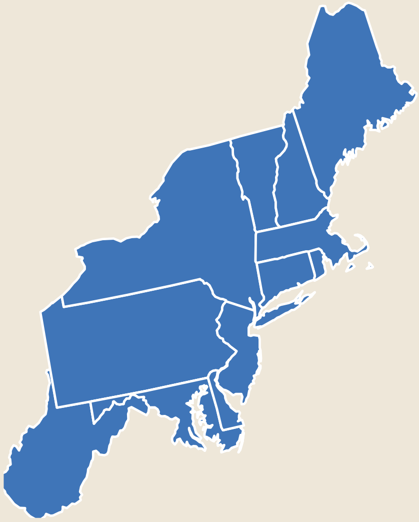

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

16 NORTHEAST

Key Messages

1. **Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.**
2. **Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.**
3. **Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.**
4. **While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.**

Sixty-four million people are concentrated in the Northeast. The high-density urban coastal corridor from Washington, D.C., north to Boston is one of the most developed environments in the world. It contains a massive, complex, and long-standing network of supporting infrastructure. The region is home to one of the world's leading financial centers, the nation's capital, and many defining cultural and historical landmarks.

The region has a vital rural component as well. The Northeast includes large expanses of sparsely populated but ecologically and agriculturally important areas. Much of the Northeast landscape is dominated by forest, but the region also has grasslands, coastal zones, beaches and dunes, and wetlands, and it is known for its rich marine and freshwater fisheries. These natural areas are essential to recreation and tourism sectors and support jobs through the sale of timber, maple syrup, and seafood. They also contribute important ecosystem services to broader populations – protecting water supplies, buffering shorelines, and sequestering carbon in soils and vegetation. The twelve Northeastern states have more than 180,000 farms, with $17 billion in annual sales.[1] The region's ecosystems and agricultural systems are tightly interwoven, and both are vulnerable to a changing climate.

Although urban and rural regions in the Northeast have profoundly different built and natural environments, both include populations that have been shown to be highly vulnerable to climate hazards and other stresses. Both also depend on aging infrastructure that has already been stressed by climate hazards including heat waves, as well as coastal and riverine flooding due to a combination of sea level rise, storm surge, and extreme precipitation events.

The Northeast is characterized by a diverse climate.[2] Average temperatures in the Northeast generally decrease to the north, with distance from the coast, and at higher elevations. Average annual precipitation varies by about 20 inches throughout the Northeast with the highest amounts observed in coastal and select mountainous regions. During winter, frequent storms bring bitter cold and frozen precipitation, especially to the north. Summers are warm and humid, especially to the south. The Northeast is often affected by extreme events such as ice storms, floods, droughts, heat waves, hurricanes, and major storms in the Atlantic Ocean off the northeast coast, referred to as nor'easters. However, variability is large in both space and

time. For example, parts of southern New England that experienced heavy snows in the cold season of 2010-2011 experienced little snow during the cold season of 2011-2012. Of course, even a season with low totals can feature costly extreme events; snowfall during a 2011 pre-Halloween storm that hit most of the Northeast, when many trees were still in leaf, knocked out power for up to 10 days for thousands of households.

Observed Climate Change

Between 1895 and 2011, temperatures in the Northeast increased by almost 2˚F (0.16˚F per decade), and precipitation increased by approximately five inches, or more than 10% (0.4 inches per decade).[3] Coastal flooding has increased due to a rise in sea level of approximately 1 foot since 1900. This rate of sea level rise exceeds the global average of approximately 8 inches (see Ch. 2: Our Changing Climate, Key Message 10; Ch. 25: Coasts), due primarily to land subsidence,[4] although recent research suggests that changes in ocean circulation in the North Atlantic – specifically, a weakening of the Gulf Stream – may also play a role.[5]

The Northeast has experienced a greater recent increase in extreme precipitation than any other region in the United States; between 1958 and 2010, the Northeast saw more than a 70% increase in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) (see Ch. 2: Our Changing Climate, Figure 2.18).[7]

Sea Level is Rising

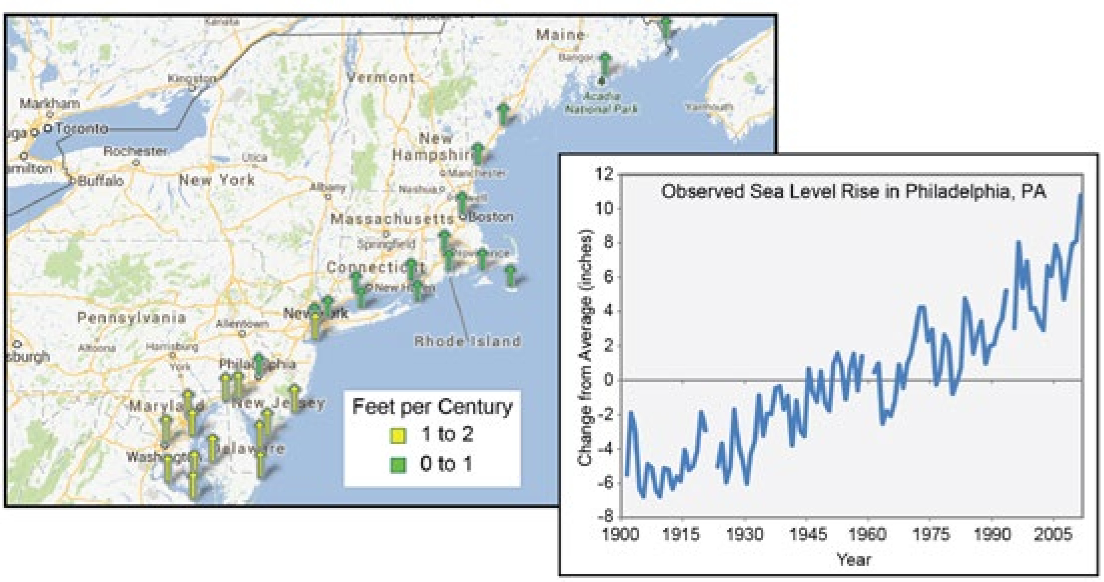

Figure 16.1. (Map) Local sea level trends in the Northeast region. Length of time series for each arrow varies by tide gauge location. (Figure source: NOAA[6]). (Graph) Observed sea level rise in Philadelphia, PA, has significantly exceeded the global average of 8 inches over the past century, increasing the risk of impacts to critical urban infrastructure in low-lying areas. Over 100 years (1901-2012), sea level increased 1.2 feet (Data from Permanent Service for Mean Sea Level).

Projected Climate Change

As in other areas, the amount of warming in the Northeast will be highly dependent on global emissions of heat-trapping gases. If emissions continue to increase (as in the A2 scenario), warming of 4.5F° to 10°F is projected by the 2080s; if global emissions were reduced substantially (as in the B1 scenario), projected warming ranges from about 3°F to 6°F by the 2080s.[3]

Under both emissions scenarios, the frequency, intensity, and duration of heat waves is expected to increase, with larger increases under higher emissions (Ch. 2: Our Changing Climate). Much of the southern portion of the region, including the majority of Maryland and Delaware, and southwestern West Virginia and New Jersey, are projected by mid-century to experience more than 60 additional days per year above 90°F compared to the end of last century under continued increases in emissions (Figure 16.2, A2 scenario). This will affect the region's vulnerable populations, infrastructure, agriculture, and ecosystems.

The frequency, intensity, and duration of cold air outbreaks is expected to decrease as the century progresses, although some research suggests that loss of Arctic sea ice could indirectly reduce this trend by modifying the jet stream and mid-latitude weather patterns.[8,9]

Projections of precipitation changes are less certain than projections of temperature increases.[3] Winter and spring precipitation is projected to increase, especially but not exclusively in the northern part of the region (Ch. 2: Our Changing Climate, Key Messages 5 and 6).[3,10] A range of model projections for the end of this century under a higher emissions scenario (A2), averaged over the region, suggests about 5% to 20% (25th to 75th percentile of model projections) increases in winter precipitation. Projected changes in summer and fall, and for the entire year, are generally small at the end of the century compared to natural variations (Ch. 2: Our Changing Climate, Key Message 5).[3] The frequency of heavy downpours is projected to continue to increase as the century progresses (Ch. 2: Our Changing Climate, Key Message 6). Seasonal drought risk is also projected to increase in summer and fall as higher temperatures lead to greater evaporation and earlier winter and spring snowmelt.[11]

Global sea levels are projected to rise 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 10),[12] depending in large part on the extent to which the Greenland and West Antarctic Ice Sheets experience significant melting. Sea level rise along most of the coastal Northeast is expected to exceed the global average rise due to local land subsidence, with the possibility of even greater regional sea level rise if the Gulf Stream weakens as some models suggest.[5,13] Sea level rise of two feet, without any changes in storms, would more than triple the frequency of dangerous coastal flooding throughout most of the Northeast.[14]

Although individual hurricanes cannot be directly attributed to climate change, Hurricanes Irene and Sandy nevertheless provided "teachable moments" by demonstrating the region's vulnerability to extreme weather events and the potential for adaptation to reduce impacts.

Projected Increases in the Number of Days over 90°F

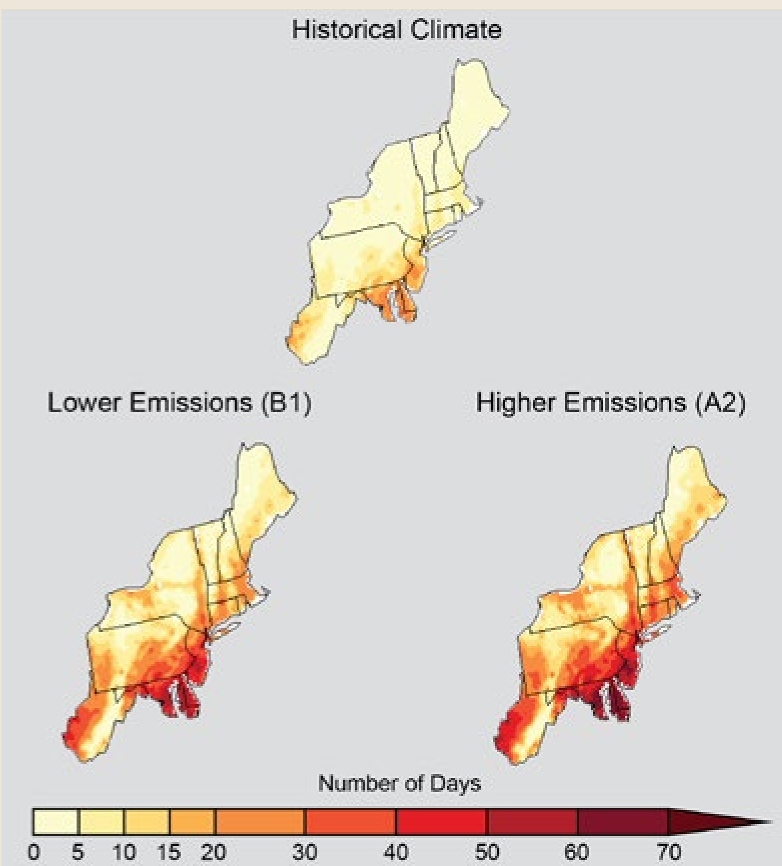

Figure 16.2. Projected increase in the number of days per year with a maximum temperature greater than 90°F averaged between 2041 and 2070, compared to 1971-2000, assuming continued increases in global emissions (A2) and substantial reductions in future emissions (B1). (Figure source: NOAA NCDC / CICS-NC).

Hurricane vulnerability

Two recent events contrast existing vulnerability to extreme events: Hurricane Irene, which produced a broad swath of very heavy rain (greater than five inches in total and sometimes two to three inches per hour in some locations) from southern Maryland to northern Vermont from August 27 to 29, 2011; and Hurricane Sandy, which caused massive coastal damage from storm surge and flooding along the Northeast coast from October 28 to 30, 2012.

Rainfall associated with Irene led to hydrological extremes in the region. These heavy rains were part of a broader pattern of wet weather preceding the storm (rainfall totals for August and September exceeded 25 inches across much of the Northeast) that left the region predisposed to extreme flooding from Irene; for example, the Schoharie Creek in New York experienced a 500-year flood.[15]

In anticipation of Irene, the New York City mass transit system was shut down, and 2.3 million coastal residents in Delaware, New Jersey, and New York faced mandatory evacuations. However, it was the inland impacts, especially in upstate New York and in central and southern Vermont, that were most severe. Ironically, many New York City residents fled to inland locations, which were harder hit. Flash flooding washed out roads and bridges, undermined railroads, brought down trees and power lines, flooded homes and businesses, and damaged floodplain forests. In Vermont, more than 500 miles of roadways and approximately 200 bridges were damaged, with estimated rebuilding costs of $175 to $250 million. Hazardous wastes were released in a number of areas, and 17 municipal wastewater treatment plants were breached by floodwaters. Agricultural losses included damage to barn structures and flooded fields of crops. Many towns and villages were isolated for days due to infrastructure impacts from river flooding (see also Ch. 5: Transportation, "Tropical Storm Irene Devastates Vermont Transportation in August 2011").[2] Affected residents suffered from increased allergen exposure due to mold growth in flooded homes and other structures and were exposed to potentially harmful chemicals and pathogens in their drinking water. In the state of Vermont, cleaning up spills from aboveground hazardous waste tanks cost an estimated $1.75 million. Septic systems were also damaged from high groundwater levels and river or stream erosion, including 17 septic system failures in the state of Vermont.[17]

Flooding and Hurricane Irene

Figure 16.3. Hurricane Irene over the Northeast on August 28, 2011. The storm, which brought catastrophic flooding rains to parts of the Northeast, took 41 lives in the United States, and the economic cost was estimated at $16 billion.[16] (Figure source: MODIS instrument on NASA's Aqua satellite).

Sandy was responsible for about 150 deaths, approximately half of which occurred in the Northeast.[18] Damages, concentrated in New Jersey, New York, and Connecticut, were estimated at $60 to $80 billion, making Sandy the second most costly Atlantic Hurricane in history behind Katrina.[19] It is also estimated that 650,000 homes were damaged or destroyed, and that 8.5 million people were without power.[18] Floodwaters inundated subway tunnels in New York City (see also Ch. 5: Transportation, "Hurricane Sandy"). Sandy also caused significant damage to the electrical grid and overwhelmed sewage treatment plants.[18] In New Jersey, repairs to damaged power and gas lines are expected to cost about $1 billion, and repairs to waste, water, and sewer systems are expected to cost $3 billion.

Many of these vulnerabilities to coastal flooding and sea level rise (Ch. 2: Our Changing Climate, Key Message 10) and intensifying storms (Ch. 2: Our Changing Climate, Key Messages 8 and 9) – including the projected frequency of flooding of tunnels and airports – were documented as early as 2001 in a report developed in support of the 2000 National Climate Assessment.[20] Despite such reports, the observed vulnerability was a surprise to many coastal residents, which suggests improved communication is needed.

Continued

Hurricane vulnerability

Over the last decade, cities, states, and agencies in the New York metropolitan region took steps to reduce their vulnerability to coastal storms.[21] In 2008, New York City convened a scientific body of experts – the New York City Panel on Climate Change (NPCC) – and formed a Climate Adaptation Task Force comprised of approximately 40 agencies, private sector companies, and regional groups. A process, approach, and tools for climate change adaptation were developed and documented in New York City[11,22] and New York State.[23] In 2012, the NPCC and Climate Adaptation Task Force were codified into New York City law, a key step towards institutionalizing climate science, impact, and adaptation assessment into long-term planning.[24]

These initiatives led to adaptation efforts, including elevating infrastructure, restoring green spaces, and developing evacuation plans that helped reduce damage and save lives during Irene and Sandy (also see discussion of Hurricane Sandy in Ch. 11: Urban). As rebuilding and recovery advances,[24] decision-making based on current and projected risks from such events by a full set of stakeholders and participants in the entire Northeast could dramatically improve resilience across the region.

Coastal Flooding Along New Jersey's Shore

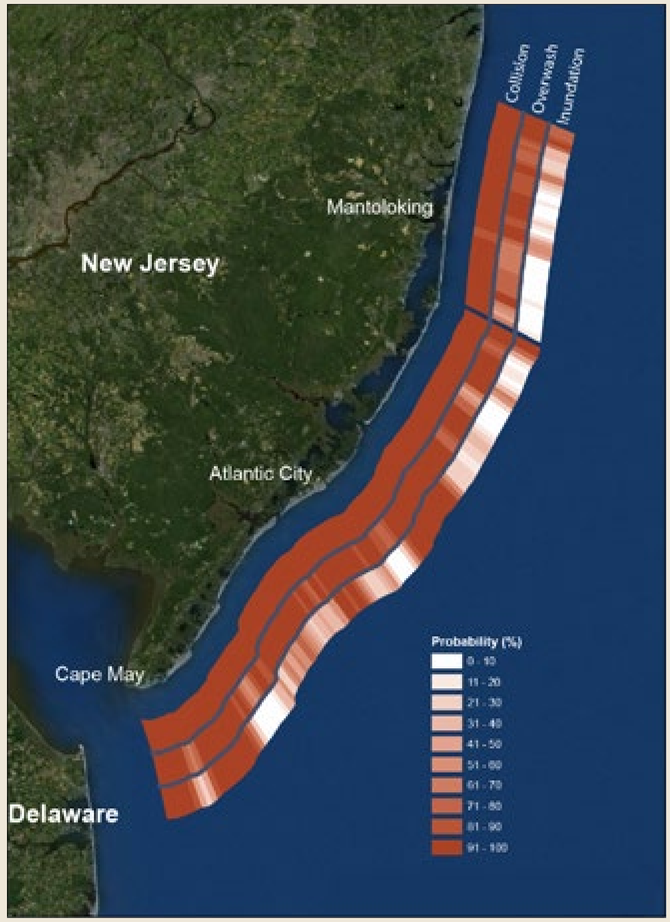

Figure 16.4. Predictions of coastal erosion prior to Sandy's arrival provided the region's residents and decision-makers with advance warning of potential vulnerability. The map shows three bands: collision of waves with beaches causing erosion on the front of the beach; overwash that occurs when water reaches over the highest point and erodes from the rear, which carries sand inland; and inundation, when the shore is severely eroded and new channels can form that lead to permanent flooding. The probabilities are based on the storm striking at high tide. For New Jersey, the model estimated that 21% of the shoreline had more than a 90% chance of experiencing inundation. These projections were realized, and made the New Jersey coastline even more vulnerable to the nor'easter that followed Hurricane Sandy by only 10 days. (Figure source: ESRI and USGS 2012[25]).

Key Message 1: Climate Risks to People

Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.

Urban residents have unique and multifaceted vulnerabilities to heat extremes. Northeastern cities, with their abundance of concrete and asphalt and relative lack of vegetation, tend to have higher temperatures than surrounding regions (the "urban heat island" effect). During extreme heat events, nighttime temperatures in the region's big cities are generally several degrees higher[26] than surrounding regions, leading to increased heat-related death among those less able to recover from the heat of the day.[27] Since the hottest days in the Northeast are often associated with high concentrations of ground-level ozone and other pollutants,[28] the combination of heat stress and poor air quality can pose a major health risk to vulnerable groups: young children, the elderly, and those with pre-existing health conditions including asthma.[29] Vulnerability is further increased as key infrastructure, including electricity for potentially life-saving air conditioning, is more likely to fail precisely when it is most needed – when demand exceeds available supply. Significant investments may be required to ensure that power generation keeps up with rising demand associated with rising temperatures.[30] Finally, vulnerability to heat waves is not evenly distributed throughout urban areas; outdoor versus indoor air temperatures, air quality, baseline health, and access to air conditioning are all dependent on socioeconomic factors.[29] Socioeconomic factors that tend to increase vulnerability to such hazards include race and ethnicity (being a minority), age (the elderly and children), gender (female), socioeconomic status (low income, status, or poverty), and education (low educational attainment). The condition of human settlements (type of housing and construction, infrastructure, and access to lifelines) and the built environment are also important determinants of socioeconomic vulnerability, especially given the fact that these characteristics influence potential economic losses, injuries, and mortality.[31]

Urban Heat Island

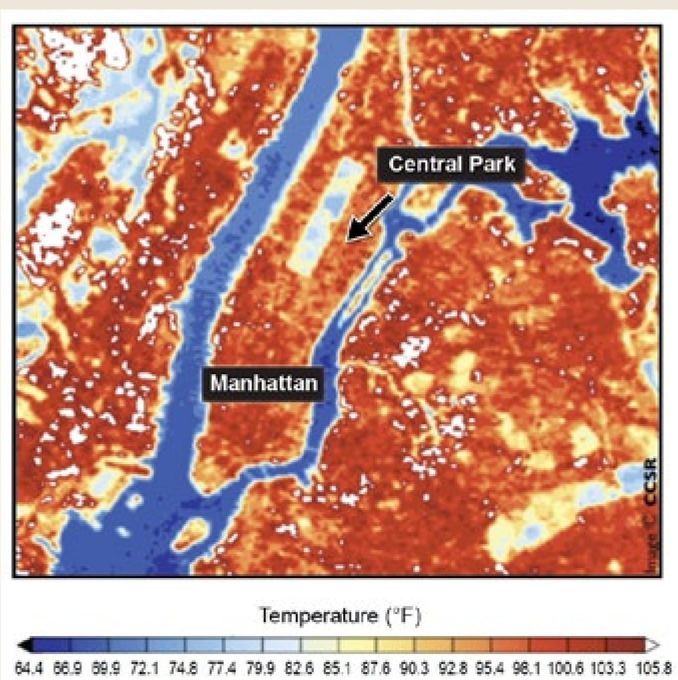

Figure 16.5. Surface temperatures in New York City on a summer's day show the "urban heat island," with temperatures in populous urban areas being approximately 10°F higher than the forested parts of Central Park. Dark blue reflects the colder waters of the Hudson and East Rivers. (Figure source: Center for Climate Systems Research, Columbia University).

Increased health-related impacts and costs, such as premature death and hospitalization due to even modest increases in heat, are predicted in the Northeast's urban centers (Ch. 9: Human Health).[32] One recent study projected that temperature changes alone would lead to a 50% to 91% increase in heat-related deaths in Manhattan by the 2080s (relative to a 1980s baseline).[33] Increased ground-level ozone due to warming is projected to increase emergency department visits for ozone-related asthma in children (0 to 17 years of age) by 7.3% by the 2020s (given the A2 scenario) relative to a 1990 baseline of approximately 650 visits in the New York metropolitan area.[34]

Heat wave research has tended to focus on urban areas, but vulnerability to heat may also become a major issue in rural areas and small towns because air conditioning is currently not prevalent in parts of the rural Northeast where heat waves have historically been rare. Some areas of northern New England, near the Canadian border, are projected to shift from having less than five to more than 15 days per year over 90°F by the 2050s under the higher emissions scenario (A2) of heat-trapping gases.[3] It should be noted that winter heating needs, a significant expense for many Northeastern residents, are likely to decrease as the century progresses.[35]

The impacts of climate change on public health will extend beyond the direct effects of temperature on human physiology. Changing distributions of temperature, precipitation, and carbon dioxide could affect the potency of plant allergens,[36] and there has been an observed increase of 13 to 27 days in the ragweed pollen season at latitudes above 44°N.[36]

Vector-borne diseases are an additional concern. Most occurrences of Lyme disease in United States are in the Northeast, especially Connecticut.[37] While it is unclear how climate change will impact Lyme disease,[38] several studies in the Northeast have linked tick activity and Lyme disease incidence to climate, specifically abundant late spring and early summer moisture.[39] West Nile Virus (WNV) is another vector-borne disease that may be influenced by changes in climate. Suitable habitat for the Asian Tiger Mosquito, which can transmit West Nile and other vector-borne diseases, is expected to increase in the Northeast from the current 5% to 16% in the next two decades and from 43% to 49% by the end of the century, exposing more than 30 million people to the threat of dense infestations by this species.[40]

Many Northeast cities, including New York, Boston, and Philadelphia, are served by combined sewer systems that collect and treat both stormwater and municipal wastewater. During heavy rain events, combined systems can be overwhelmed and untreated water may be released into local water bodies. In Connecticut, the risk for contracting a stomach illness while swimming significantly increased after a one inch precipitation event,[41] and studies have found associations between diarrheal illness among children and sewage discharge in Milwaukee.[42] More frequent heavy rain events could therefore increase the incidence of waterborne disease.

Historical settlement patterns and ongoing investment in coastal areas and along major rivers combine to increase the vulnerabilities of people in the Northeast to sea level rise and coastal storms. Of the Northeast's population of 64 million,[43] approximately 1.6 million people live within the Federal Emergency Management Agency's (FEMA) 100-year coastal flood zone, with the majority – 63% of those at risk – residing in New York and New Jersey.[44] As sea levels rise, populations in the current 1-in-100-year coastal flood zone (defined as the area with at least a 1% chance of experiencing a coastal flood in a given year) will experience more frequent flooding, and populations that have historically fallen outside the 1-in-100-year flood zone will find themselves in that zone. People living in coastal flood zones are vulnerable to direct loss of life and injury associated with tropical storms and nor'easters. Flood damage to personal property, businesses, and public infrastructure can also result (see Key Message 2).

This risk is not limited to the 1-in-100-year flood zone; in the Mid-Atlantic part of the region alone, estimates suggest that between 450,000 and 2.3 million people are at risk from a three foot sea level rise,[45] which is in the range of projections for this century.

Throughout the Northeast, populations are also concentrated along rivers and their flood plains. In mountainous regions, including much of West Virginia and large parts of Pennsylvania, New York, Vermont, and New Hampshire, more intense precipitation events (Ch. 2: Our Changing Climate)[3] will mean greater flood risk, particularly in valleys, where people, infrastructure, and agriculture tend to be concentrated.

Key Message 2: Stressed Infrastructure

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.

Disruptions to services provided by public and private infrastructure in the Northeast both interrupt commerce and threaten public health and safety (see also Ch. 11: Urban).[46] In New York State, two feet of sea level rise is estimated (absent adaptation investment) to flood or render unusable 212 miles of roads, 77 miles of rail, 3,647 acres of airport facilities, and 539 acres of runways.[47] Port facilities, such as in Maryland (primarily Baltimore), also have flooding impact estimates: 298 acres, or 32% of the overall port facilities in the state.[47] These impacts have potentially significant economic ramifications. For example, in 2006 alone the Port of Baltimore generated more than 50,200 jobs, $3.6 billion in personal income, $1.9 billion in business revenues, and $388 million in state, county, and municipal tax.[48] The New York City Panel on Climate Change highlighted a broader range of climate impacts on infrastructure sectors (see Table 16.1).[11] Although this study focused specifically on New York City, these impacts are applicable throughout the region. Predicted impacts of coastal flooding on infrastructure were largely borne out by Hurricane Sandy; sea level rise will only increase these vulnerabilities.

The more southern states within the region, including Delaware and Maryland, have a highly vulnerable land area because of a higher rate of sea level rise and relatively flat coastlines compared to the northern tier. The northern states, including Massachusetts, Rhode Island, and Connecticut, have less land area exposed to a high inundation risk because of a lower relative sea level rise and because of their relatively steep coastal terrain.[49] Still, low-lying coastal metropolitan areas in New England have considerable infrastructure at risk. In Boston alone, cumulative damage to buildings and building contents, as well as the associated emergency costs, could potentially be as high as $94 billion between 2000 and 2100, depending on the sea level rise scenario and which adaptive actions are taken.[50]

Table 16.1. Impacts of sea level rise and coastal floods on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig 2010,[51] Zimmerman and Faris 2010,[52] and Ch. 25: Coasts.

Communications	Energy	Transportation	Water and Waste
Higher average sea level			
• Increased saltwater encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance costs and shortened replacement cycles • Cellular tower destruction or loss of function	• Increased coastal erosion rates and/or permanent inundation of low-lying areas, threatening coastal power plants • Increased equipment damage from corrosive effects of saltwater encroachment, resulting in higher maintenance costs and shorter replacement cycles	• Increased saltwater encroachment and damage to infrastructure not built to withstand saltwater exposure • Increased coastal erosion rates and/or permanent inundation of low-lying areas, resulting in increased maintenance costs and shorter replacement cycles • Decreased clearance levels under bridges	• Increased saltwater encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure • Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownfields, and waste storage facilities • Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations • Increased saltwater infiltration into freshwater distribution systems
More frequent and intense coastal flooding			
• Increased need for emergency management actions with high demand on communications infrastructure • Increased damage to communications equipment and infrastructure in low-lying areas	• Increased need for emergency management actions • Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action • Increased use of energy to control floodwaters • Increased number and duration of local outages due to flooded and corroded equipment	• Increased need for emergency management actions • Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to infrastructure due to wave action • Decreased levels of service from flooded roadways; increased hours of delay from congestion during street flooding episodes • Increased energy use for pumping	• Increased need for emergency management actions • Exacerbated street, basement, and sewer flooding, leading to structural damage to infrastructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

Coney Island after Hurricane Irene

Figure 16.6. Flooded subway tracks in Coney Island after Hurricane Irene. (Photo credit: Metropolitan Transportation Authority of the State of New York 2011).

In the transportation sector (see also Ch. 5: Transportation), many of the region's key highways (including I-95) and rail systems (including Amtrak and commuter rail networks) span areas that are prone to coastal flooding. In addition to temporary service disruptions, storm surge flooding can severely undermine or disable critical infrastructure along coasts, including subway systems, wastewater treatment plants, and electrical substations. Saltwater corrosion can damage sensitive and critical electrical equipment, such as electrical substations for energy distribution and signal equipment for rail systems; corrosion also accelerates rust damage on rail lines. Saltwater also threatens groundwater supplies and damages wastewater treatment plants.

Key Message 3: Agricultural and Ecosystem Impacts

Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.

Farmers in the Northeast are already experiencing consequences of climate change. In addition to direct crop damage from increasingly intense precipitation events, wet springs can delay planting for grain and vegetables in New York, for example, and subsequently delay harvest dates and reduce yields.[53] This is an issue for agriculture nationally,[54] but is particularly acute for the Northeast, where heavy rainfall events have increased more than in any other region of the country (Ch. 2: Our Changing Climate, Key Message 6).[7] In the future, farmers may also face too little water in summer to meet increased crop water demand as summers become hotter and growing seasons lengthen.[55,56] Increased frequency of summer heat stress is also projected, which can negatively affect crop yields and milk production.[57]

Despite a trend toward warmer winters, the risk of frost and freeze damage continues, and has paradoxically increased over the past decade (see also Ch. 8: Ecosystems). These risks are exacerbated for perennial crops in years with variable winter temperatures. For example, midwinter-freeze damage cost wine grape growers in the Finger Lakes region of New York millions of dollars in losses in the winters of 2003 and 2004.[58] This was likely due to de-hardening of the vines during an unusually warm December, which increased susceptibility to cold damage just prior to a subsequent hard freeze. Another avenue for cold damage, even in a relatively warm winter, is when there is an extended warm period in late winter or early spring causing premature leaf-out or bloom, followed by a damaging frost event, as occurred throughout the Northeast in 2007[59] and again in 2012 when apple, grape, cherry, and other fruit crops were hard hit.[60]

Increased weed and pest pressure associated with longer growing seasons and warmer winters will be an increasingly important challenge; there are already examples of earlier arrival and increased populations of some insect pests such as corn earworm.[57] Furthermore, many of the most aggressive weeds, such as kudzu, benefit more than crop plants from higher atmospheric carbon dioxide, and become more resistant to herbicide control.[61] Many weeds respond better than most cash crops to increasing carbon dioxide concentrations, particularly "invasive" weeds with the so-called C_3 photosynthetic pathway, and with rapid and expansive growth patterns, including large allocations of below-ground biomass, such as roots.[62] Research also suggests that glyphosate (for example, Roundup), the most widely-used herbicide in the United States, loses its efficacy on weeds grown at the increased carbon dioxide levels likely to occur in the coming decades.[63] To date, all weed/crop competition studies where the photosynthetic pathway is the same for both species favor weed growth over crop growth as carbon dioxide is increased.[61]

Effects of rising temperatures on the Northeast's ecosystems have already been clearly observed (see also Ch. 8: Ecosystems). Further, changes in species distribution by elevation are occurring; a Vermont study found an upslope shift of 299 to 390 feet in the boundary between northern hardwoods and boreal forest on the western slopes of the Green Mountains between 1964 and 2004.[64] Wildflowers[65] and woody perennials are blooming earlier [66] and migratory birds are arriving sooner.[67] Because species differ in their ability to adjust, asynchronies (like a mismatch between key food source availability and migration patterns) can develop, increasing species and ecosystem vulnerability. Several bird species have expanded their ranges northward[68] as have some invasive insect species, such as the hemlock woolly adelgid,[69] which has devastated hemlock trees. Warmer winters and less snow cover in recent years have contributed to increased deer populations[70] that degrade forest understory vegetation.[71]

As ocean temperatures continue to rise, the range of suitable habitat for many commercially important fish and shellfish species is projected to shift northward. For example, cod and lobster fisheries south of Cape Cod are projected to have significant declines.[72] Although suitable habitats will be shrinking for some species (such as coldwater fish like brook trout) and expanding for others (such as warmwater fish like bass), it is difficult to predict what proportion of species will be able to move or adapt as their optimum climate zones shift.[73] As each species responds uniquely to climate change, disruptions of important species interactions (plants and pollinators; predators and prey) can be expected. For example, it is uncertain what forms of vegetation will move into the Adirondack Mountains when the suitable habitat for spruce-fir forests disappears.[74] Increased productivity of some northern hardwood trees in the Northeast is projected (due to longer growing seasons and assuming a significant benefit from higher atmospheric carbon dioxide), but summer drought and other extreme events may offset potential productivity increases.[75] Range shifts in traditional foods gathered from the forests by Native American communities, such as Wabanaki berries in the Northeast, can have negative health and cultural impacts (Ch. 12: Indigenous Peoples).[76]

In contrast, many insect pests, pathogens, and invasive plants like kudzu appear to be highly and positively responsive to recent and projected climate change.[77] Their expansion will lead to an overall loss of biodiversity, function, and resilience of some ecosystems.

The Northeast's coastal ecosystems and the species that inhabit them are highly vulnerable to rising seas (see also Ch. 25: Coasts, Key Message 4). Beach and dune erosion, both a cause and effect of coastal flooding, is also a major issue in the Northeast.[78,79] Since the early 1800s, there has been an estimated 39% decrease in marsh coverage in coastal New England; in the metropolitan Boston area, marsh coverage is estimated to be less than 20% of its late 1700s value.[80] Impervious urban surfaces and coastal barriers such as seawalls limit the ability of marshes to expand inland as sea levels rise.[81]

The Chesapeake Bay

The Chesapeake Bay is the largest U.S. estuary, with a drainage basin that extends over six states. It is a critical and highly integrated natural and economic system threatened by changing land-use patterns and a changing climate – including sea level rise, higher temperatures, and more intense precipitation events. The ecosystem has a central role in the economy, including providing sources of food for people and the region's other inhabitants, and cooling water for the energy sector. It also provides critical ecosystem services.

As sea levels rise, the Chesapeake Bay region is expected to experience an increase in coastal flooding and drowning of estuarine wetlands. The lower Chesapeake Bay is especially at risk due to high rates of sinking land (known as subsidence).[82] Climate change and sea level rise are also likely to cause a number of ecological impacts, including declining water quality and clarity, increases in harmful algae and low oxygen (hypoxia) events, decreases in a number of species including eelgrass and seagrass beds, and changing interactions among trophic levels (positions in the food chain) leading to an increase in subtropical fish and shellfish species in the bay.[83]

Key Message 4: Planning and Adaptation

While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Of the 12 states in the Northeast, 11 have developed adaptation plans for several sectors and 10 have released, or plan to release, statewide adaptation plans.[84] Given the interconnectedness of climate change impacts and adaptation, multi-state coordination could help to ensure that information is shared efficiently and that emissions reduction and adaptation strategies do not operate at cross-purposes.

Local and state governments in the Northeast have been leaders and incubators in utilizing legal and regulatory opportunities to foster climate change policies.[85] The Regional Greenhouse Gas Initiative (RGGI) was the first market-based regulatory program in the U.S. aimed at reducing greenhouse gas emissions; it is a cooperative effort among nine northeastern states.[86] Massachusetts became the first state to officially incorporate climate change impacts into its environmental review procedures by adopting legislation that directs agencies to "consider reasonably foreseeable climate change impacts, including additional greenhouse gas emissions, and effects, such as predicted sea level rise."[87] In addition, Maine, Massachusetts, and Rhode Island have each adopted some form of "rolling easement" to ensure that wetlands or dunes migrate inland as sea level rises and reduce the risk of loss of life and property.[45]

Connecticut Coastline and Expanding Salt Marshes

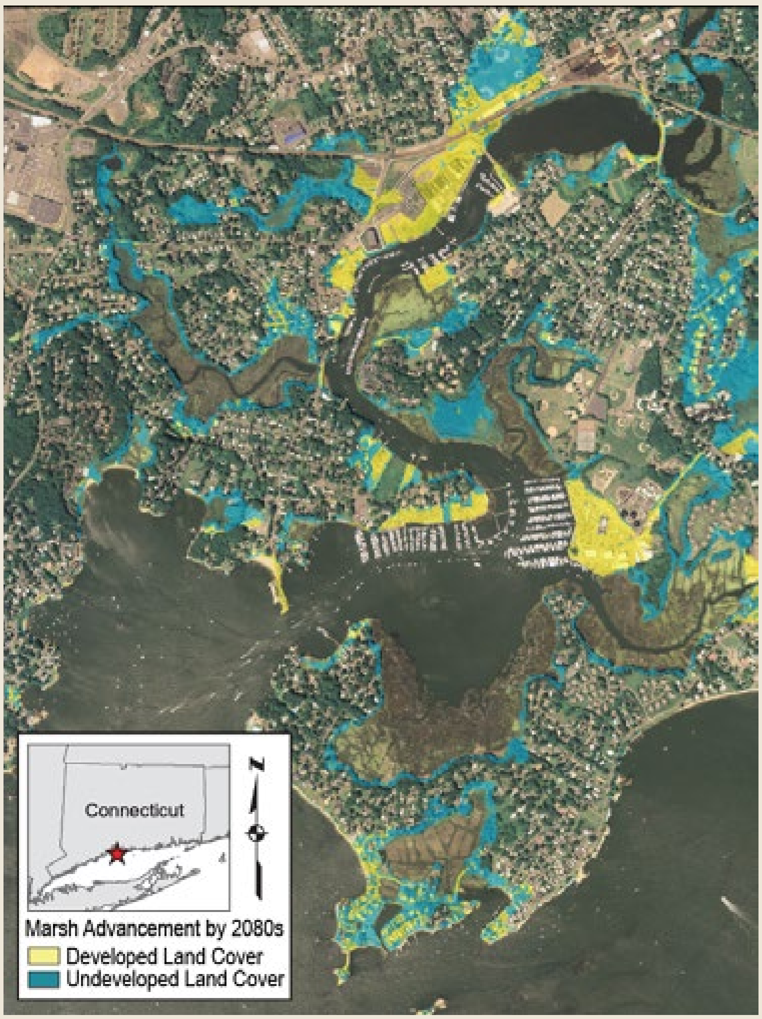

Figure 16.7. The Nature Conservancy's adaptation decision-support tool (www.coastalresilience.org)[88] depicts building-level impacts due to inundation (developed land cover, yellow areas) and potential marsh advancement zones (undeveloped land cover – currently forest, grass, and agriculture – blue areas) using downscaled sea level rise projections (52 inches by 2080s depicted) along the Connecticut and New York coasts. (Figure source: Ferdaña et al. 2010,[90] Beck et al. 2013[89]).

Northeast cities have employed a variety of mechanisms to respond to climate change, including land-use planning, provisions to protect infrastructure, regulations related to the design and construction of buildings, and emergency preparation, response, and recovery.[91] While significant progress has been made, local governments still face limitations of legal authority, geographic jurisdiction, and resource constraints that could be addressed through effective engagement and support from higher levels of government.

Keene, New Hampshire, has been a pilot community for ICLEI's Climate Resilient Communities program for adaptation planning[92] – a process implemented through innovative community engagement methods.[93] The Cape Cod Commission is another example in New England; the Commission has drafted model ordinances to help communities incorporate climate into zoning decision-making. Farther south, New York City has taken numerous steps to implement PlaNYC, a far-reaching sustainability plan for the city, including amending the construction code and the zoning laws and the implementation of measures focused on developing adaptation strategies to protect the City's public and private infrastructure from the effects of climate change;[24] some major investments in protection have even been conceptualized.

Storm Surge Barrier

Figure 16.8. Conceptual design of a storm surge barrier in New York City. (Figure source: Jansen and Dircke 2009).

One widely used adaptation-planning template is the eight-step iterative approach developed by the New York City Panel on Climate Change; it was highlighted in the contribution of the National Academy of Science's Adaptation Panel to America's Climate Choices and adopted by the Committee on America's Climate Choices. It describes a procedure that decision-makers at all levels can use to design a flexible adaptation pathway to address infrastructure and other response issues through inventory and assessment of risk. The key, with respect to infrastructure, is to link adaptation strategies with capital improvement cycles and adjustment of plans to incorporate emerging climate projections[11,94] – but the insights are far more general than that (see the Adaptation Panel Report[95]).

In most cases, adaptation requires information and tools coupled to a decision-support process steered by strong leadership, and there are a growing number of examples in the Northeast. At the smaller, municipal scale, coastal pilot projects in Maryland,[96] Delaware,[97] New York, and Connecticut[90] are underway.

Research and outreach efforts are underway in the region to help farmers find ways to cope with a rapidly changing climate, take advantage of a longer growing season, and reduce greenhouse gas emissions,[56,98] but unequal access to capital and information for strategic adaptation and mitigation remain a challenge. Financial barriers can constrain farmer adaptation.[99] Even relatively straightforward adaptations such as changing varieties are not always a low-cost option. Seed for new stress-tolerant varieties is sometimes expensive or regionally unavailable, and new varieties often require investments in new planting equipment or require adjustment in a wide range of farming practices. Investment in irrigation and drainage systems are relatively expensive options, and a challenge for farmers will be determining when the frequency of yield losses due to summer water deficits or flooding has or will become frequent enough to warrant such capital investments.

Regional activities in the Northeast are also being linked to federal efforts. For example, NASA's Agency-wide Climate Adaptation Science Investigator Workgroup (CASI) brings together NASA facilities managers with NASA climate scientists in local Climate Resilience Workshops. This approach was in evidence at the Goddard Space Flight Center in Maryland, where scientists helped institutional managers address energy and stormwater management vulnerabilities.

Maine's culverts: an adaptation case study

Culverts and the structures they protect are receiving increasing attention, since they are vulnerable to damage during the types of extreme precipitation events that are occurring with increasing frequency in the Northeast (Ch. 2: Our Changing Climate, Key Message 6; Ch. 5: Transportation). For instance, severe storms in the Northeast that were projected in the 1950s to occur only once in 100 years, now are projected to occur once every 60 years.[100]

The Maine Department of Transportation manages more than 97,000 culverts, but individual property owners or small towns manage even more; Scarborough, Maine, for example, has 2,127 culverts. When 71 town managers and officials in coastal Maine were surveyed as part of the statewide Sustainability Solutions Initiative, culverts, with their 50 to 65 year expected lifespan, emerged atop a wish list for help in adapting to climate change.[101]

A research initiative that mapped decisions by town managers in Maine to sources of climate information, engineering design, mandated requirements, and calendars identified the complex, multi-jurisdictional challenges of widespread adaptation for even such seemingly simple actions as using larger culverts to carry water from major storms.[101] To help towns adapt culverts to expected climate change over their lifetimes, the Sustainability Solutions Initiative is creating decision tools to map culvert locations, schedule maintenance, estimate needed culvert size, and analyze replacement needs and costs.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
Results of the Northeast Regional Climate assessment workshop that was held on November 17-18, 2011, at Columbia University, with approximately 60 attendees, were critically important in our assessment. The workshop was the beginning of the process that led to the foundational Technical Input Report (TIR).[2] That 313-page report consisted of seven chapters by 13 lead authors and more than 60 authors in total. Public and private citizens or institutions who service and anticipate a role in maintaining support for vulnerable populations in Northeast cities and communities indicated that they are making plans to judge the demand for adaptation services. These stakeholder interactions were surveyed and engaged in the preparation of this chapter. We are confident that the TIR authors made a vigorous attempt to engage various agencies at the state level and non-governmental organizations (NGOs) that have broader perspectives.

The author team engaged in multiple technical discussions via teleconferences, which included careful review of the foundational TIR[2] and approximately 50 additional technical inputs provided by the public, as well as the other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each key message.

Key message #1 Traceable Account

Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the Northeast Technical Input Report.[2] Nearly 50 Technical Input reports, on a wide range of topics, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications (including many that are not cited) describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation and river flooding for the Northeast. For sea level rise (SLR), the authors relied on the NCA SLR scenario[12] and research by the authors on the topic (for example, Horton et al. 2010[51]). Recent work[26] summarizes the literature on heat islands and extreme events. For a recent study on climate in the Northeast,[3] the authors worked closely with the region's state climatologists on both the climatology and projections.

The authors also considered many recent peer-reviewed publications[29,32,34,44] that describe how human vulnerabilities to climate hazards in the region can be increased by socioeconomic and other factors. Evaluating coupled multi-system vulnerabilities is an emerging field; as a result, additional sources including white papers[3] have informed this key message as well.

To capture key issues, concerns, and opportunities in the region, various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) and Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf).

New information and remaining uncertainties
Important new evidence (cited above) confirmed many of the findings from a prior Northeast assessment[10] (see http://nca2009.globalchange.gov/northeast).

The evidence included results from improved models and updated observational data (for example, Liu et al. 2012; Parris et al. 2012; Sallenger et al. 2012[5,9,12]). The current assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm its relevance and significance for local decision-makers; examples include a Northeast Listening Session in West Virginia, a kickoff meeting in New York City, and New York City Panel on Climate Change meetings.

There is wide diversity of impacts across the region driven by both exposure and sensitivity that are location and socioeconomic context specific. Future vulnerability will be influenced by changes in demography, economics, and policies (development and climate driven) that are difficult to predict and dependent on international and national considerations. Another uncertainty is the potential for adaptation strategies (and to a lesser extent mitigation) to reduce these vulnerabilities.

There are also uncertainties associated with the character of the interconnections among systems, and the positive and negative synergies. For example, a key uncertainty is how systems will respond during extreme events and how people will adjust their short- to long-term planning to take account of a dynamic climate. Such events are, by definition, manifestations of historically rare and therefore relatively undocumented climatology which represent uncertainty in the exposure to climate risk. Nonetheless, these events are correlated, when considered holistically, with climate change driven to some degree by human interference with the climate system. There are uncertainties in exposure.

There are also uncertainties associated with sensitivity to future changes driven to some (potentially significant) degree by non-climate stressors, including background health of the human population and development decisions. Other uncertainties include how much effort will be put into making systems more resilient and the success of these efforts. Another critical uncertainty is associated with the climate system itself.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is:

Very high for sea level rise and coastal flooding as well as heat waves.

High for intense precipitation events and riverine flooding.

Very high for both added stresses on environmental, social, and economic systems and for increased vulnerability, especially for populations that are already most disadvantaged.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.

Description of evidence base

The key message summarizes extensive evidence documented in the Northeast Technical Input Report (TIR).[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

To capture key issues, concerns and opportunities in the region, various regional assessments were also consulted, such as PlaNYC (http://www.nyc.gov/html/planyc2030) and Boston's Climate Plan (http://www.cityofboston.gov/Images_Documents/A%20Climate%20of%20Progress%20-%20CAP%20Update%202011_tcm3-25020.pdf).

In addition, a report by the U.S. Department of Transportation[47] provided extensive documentation that augmented an NGO report.[102] Other sources that support this key message include Horton and Rosenzweig, 2010, Rosenzweig et al. 2011, and Zimmerman and Faris, 2010.[23,51,52]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the prior Northeast assessment: (http://nca2009.globalchange.gov/northeast) which informed the prior NCA.[10]

The new sources above relied on improved models that have been calibrated to new observational data across the region.

It is important to note, of course, that there is wide diversity across the region because both exposure and sensitivity are location- and socioeconomic-context-specific. The wisdom derived from many previous assessments by the National Academy of Sciences, the New York Panel on Climate Change, and the 2009 National Climate Assessment[10,11,95] indicates that future vulnerability at any specific location will be influenced by changes in demography, economics, and policy. These changes are difficult to predict at local scales even as they also depend on international and national considerations. The potential for adaptation strategies (and to a lesser extent mitigation) to reduce these vulnerabilities is yet another source of uncertainty that expands as the future moves into the middle of this century.

Assessment of confidence based on evidence

We have **very high** confidence in projected sea level rise and increased coastal flooding, and **high** confidence for increased intense precipitation events. This assessment of confidence is based on our review of the literature and submitted input and has been defended internally and externally in conversation with local decision-makers and representatives of interested NGOs, as well as the extensive interactions with stakeholders across the region reported in the Northeast TIR.[2]

Very high confidence that infrastructure will be increasingly compromised, based on the clear evidence of impacts on current infrastructure from hazards such as Hurricane Irene, and from the huge deficit of needed renewal identified by a diverse engineering community.[46]

Key message #3 Traceable Account

Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts. Farmers can explore new crop options, but these adaptations are not cost- or risk-free. Moreover, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.

Description of evidence base

The key message summarizes extensive evidence documented in the Northeast Technical Input Report.[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. The Traceable Account for Key Message 1 provides the evidence base on sea level rise, flooding, and precipitation.

Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region with particular focus on managed (agriculture and fisheries) and unmanaged (ecosystems) systems (for example, Buonaiuto et al. 2011; Wolfe et al. 2011[56,70,78]).

Species and ecosystem vulnerability have been well documented historically in numerous peer-reviewed papers in addition to the ones cited in the TIR.[2] There have also been many examples of impacts on agriculture of climate variability and change in the Northeast (for example, Wolfe et al. 2008[57]). Most note that there is potential for significant benefits associated with climate changes to partially offset expected negative outcomes for these managed systems (for example, Hatfield et al. 2011[54])

New information and remaining uncertainties

Important new evidence (cited above, plus Najjar et. al. 2010,[83] for example) confirmed many of the findings from the prior Northeast assessment (http://nca2009.globalchange.gov/northeast) which informed the 2009 NCA.[10] These new sources also relied on improved models that have been calibrated to new observational data across the region.

Agriculture, fisheries, and ecosystems in the Northeast are strongly linked to climate change and to other changes occurring outside the region and beyond the boundaries of the United States. These changes can influence the price of crops and agricultural inputs such as fertilizer, for example, as well as the abundance of ecosystem and agricultural pests and the abundance and range of fish stocks. Other uncertainties include imprecise understandings of how complex ecosystems will respond to climate- and non-climate-induced changes and the extent to which organisms may be able to adapt to a changing climate.

Assessment of confidence based on evidence

Based on our assessment, we have **very high** confidence for climate impacts (especially sea level rise and storm surge) on ecosystems; and we have **high** confidence for climate impacts on agriculture (reduced to some degree, compared to our level of confidence about ecosystems, by uncertainty about the efficacy and implementation of adaptation options). Confidence in fisheries changes is **high** since confidence in both ocean warming and fish sensitivity to temperature is **high**.

Key message #4 Traceable Account

While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages.

Description of evidence base

The key message relies heavily on extensive evidence documented in the Northeast Technical Input Report (TIR).[2] Technical Input reports (48) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input. Many of the key references cited in the TIR reflected experiences and processes developed in iterative stakeholder engagement concerning risk management[94,103] that have been heavily cited and employed in new venues – local communities like Keane (NH) and New York City, for example.

Various regional assessments were also consulted to capture key issues, concerns and opportunities in the region (for example, for Delaware, Maine, Maryland, and Long Island, NY). In addition, there have been agency and government white paper reports describing proposed adaptation strategies based on climate impact assessments.[11,90] We discovered that 10 of the 12 states in the Northeast have statewide adaptation plans in place or under development (many plans can be found at: http://georgetownclimate.org/node/3324).

New information and remaining uncertainties

That most Northeast states have begun to plan for adaptation is a matter of record. That few adaptation plans have been implemented is confirmed in Technical Inputs submitted to the National Climate Assessment process as well as prior assessments (http://nca2009.globalchange.gov/northeast), which informed the 2009 NCA.[10]

Key uncertainties looking forward include: 1) the extent to which proposed adaptation strategies will be implemented given a range of factors including competing demands and limited funding; 2) the role of the private sector and individual action in adaptation, roles which can be difficult to document; 3) the extent of the federal role in adaptation planning and implementation; and 4) how changes in technology and the world economy may change the feasibility of specific adaptation strategies.[11]

Assessment of confidence based on evidence

This Key Message is simply a statement of observed fact, so confidence language is not applicable.

Climate Change Impacts in the United States

CHAPTER 17
SOUTHEAST AND THE CARIBBEAN

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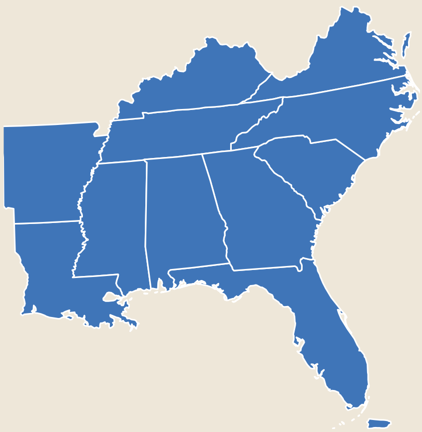

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On the Web: http://nca2014.globalchange.gov/report/regions/southeast

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

17 SOUTHEAST AND THE CARIBBEAN

Key Messages

1. **Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.**
2. **Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.**
3. **Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.**

The Southeast and Caribbean are exceptionally vulnerable to sea level rise, extreme heat events, hurricanes, and decreased water availability. The geographic distribution of these impacts and vulnerabilities is uneven, since the region encompasses a wide range of natural system types, from the Appalachian Mountains to the coastal plains. It is also home to more than 80 million people[1] and draws millions of visitors every year. In 2009, Puerto Rico hosted 3.5 million tourists who spent $3.5 billion.[2] In 2012, Louisiana and Florida alone hosted more than 115 million visitors.[3]

The region has two of the most populous metropolitan areas in the country (Miami and Atlanta) and four of the ten fastest-growing metropolitan areas.[1] Three of these (Palm Coast, FL, Cape Coral-Fort Myers, FL, and Myrtle Beach area, SC) are along the coast and are vulnerable to sea level rise and storm surge. Puerto Rico has one of the highest population densities in the world, with 56% of the population living in coastal municipalities.[4]

The Gulf and Atlantic coasts are major producers of seafood and home to seven major ports[5] that are also vulnerable. The Southeast is a major energy producer of coal, crude oil, and natural gas, and is the highest energy user of any of the National Climate Assessment regions.[5]

The Southeast's climate is influenced by many factors, including latitude, topography, and proximity to the Atlantic Ocean

Billion Dollar Weather/Climate Disasters

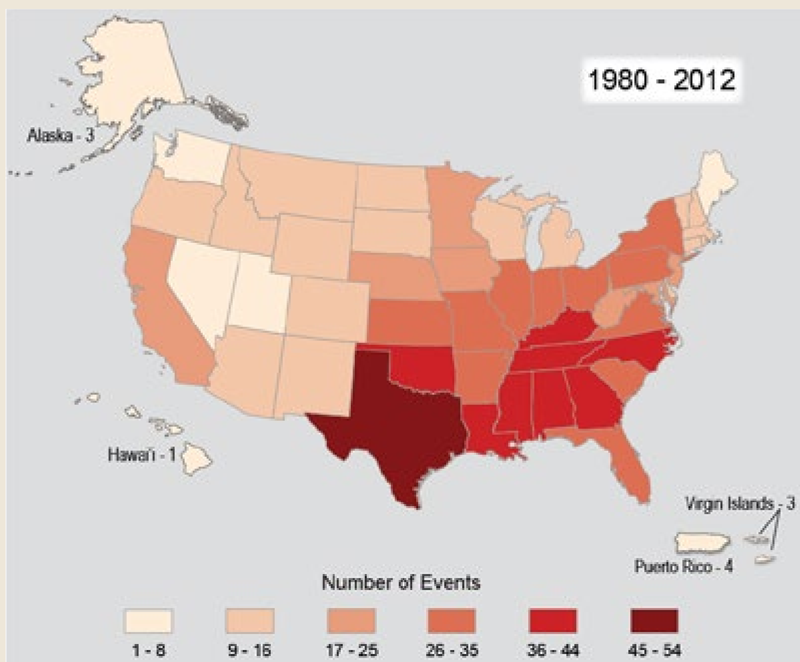

Figure 17.1. This map summarizes the number of times each state has been affected by weather and climate events over the past 30 years that have resulted in more than a billion dollars in damages. The Southeast has been affected by more billion-dollar disasters than any other region. The primary disaster type for coastal states such as Florida is hurricanes, while interior and northern states in the region also experience sizeable numbers of tornadoes and winter storms. For a list of events and the affected states, see: http://www.ncdc.noaa.gov/billions/events.[6] (Figure source: NOAA NCDC).

Stories of change: coastal louisiana tribal communities

Climate change impacts, especially sea level rise and related increases in storm surges pulsing farther inland, will continue to exacerbate ongoing land loss already affecting Louisiana tribes. Four Native communities in Southeast Louisiana (Grand Bayou Village, Grand Caillou/Dulac, Isle de Jean Charles, and Pointe-au-Chien) have already experienced significant land loss. Management of river flow has deprived the coastal wetlands of the freshwater and sediment that they need to replenish and persist. Dredging of canals through marshes for oil and gas exploration and pipelines has led to erosion and intense saltwater intrusion, resulting in additional land loss. Due to these and other natural and man-made problems, Louisiana has lost 1,880 square miles of land in the last 80 years.[8] This combination of changes has resulted in a cascade of losses of sacred places, healing plants, habitat for important wildlife, food security,[9] and in some cases connectivity with the mainland. Additional impacts include increased inundation of native lands, further travel to reach traditional fishing grounds, reduced connections among family members as their lands have become more flood-prone and some have had to move, and declining community cohesiveness as heat requires more indoor time.[10] (For more specifics, see Ch. 12: Indigenous Peoples). Numerous other impacts from increases in temperature, sea level rise, land loss, erosion, subsidence, and saltwater intrusion amplify these existing problems.

Shrinking Lands for Tribal Communities

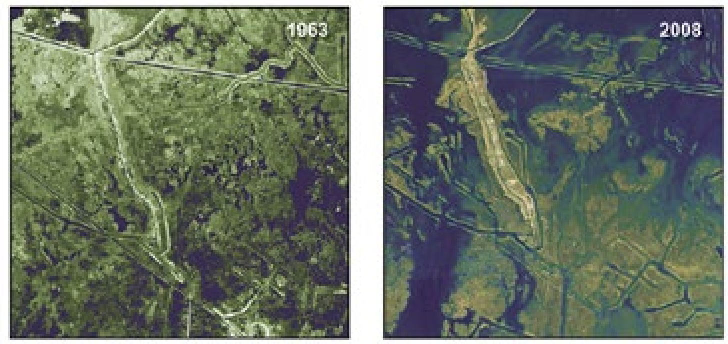

Figure 17.2. Aerial photos of Isle de Jean Charles in Louisiana taken 25 years apart shows evidence of the effects of rising seas, sinking land, and human development. The wetlands adjacent to the Isle de Jean Charles community (about 60 miles south of New Orleans) have been disappearing rapidly since the photo on the left was taken in 1963. By 2008, after four major hurricanes, significant erosion, and alteration of the surrounding marsh for oil and gas extraction, open water surrounds the greatly reduced dry land. See Ch. 25: Coasts for more information. (Photo credit: USGS).

and the Gulf of Mexico. Temperatures generally decrease northward and into mountain areas, while precipitation decreases with distance from the Gulf and Atlantic coasts. The region's climate also varies considerably over seasons, years, and decades, largely due to natural cycles such as the El Niño-Southern Oscillation (ENSO – periodic changes in ocean surface temperatures in the Tropical Pacific Ocean), the semi-permanent high pressure system over Bermuda, differences in atmospheric pressure over key areas of the globe, and land-falling tropical weather systems.[7] These cycles alter the occurrences of hurricanes, tornadoes, droughts, flooding, freezing winters, and ice storms, contributing to climate and weather disasters in the region that have exceeded the total number of billion dollar disasters experienced in all other regions of the country combined (see Figure 17.1).

Observed and Projected Climate Change

Average annual temperature during the last century across the Southeast cycled between warm and cool periods (see Figure 17.3, black line). A warm peak occurred during the 1930s and 1940s followed by a cool period in the 1960s and 1970s. Temperatures increased again from 1970 to the present by an average of 2°F, with higher average temperatures during summer months. There have been increasing numbers of days above 95°F and nights above 75°F, and decreasing numbers of extremely cold days since 1970.[11] The Caribbean also exhibits a trend since the 1950s, with increasing numbers of very warm days and nights, and with daytime maximum temperatures above 90°F and nights above 75°F.[4] Daily and five-day rainfall intensities have also increased.[5] Also, summers have been either increasingly dry or extremely wet.[11] For the Caribbean, precipitation trends are unclear, with some regions experiencing smaller annual amounts of rainfall and some increasing amounts.[4] Although the number of major tornadoes has increased over the last 50 years, there is no statistically significant trend (Ch 2: Our Changing Climate, Key Message 9).[11,12] This increase may be attributable to better reporting of tornadoes. The number of Category 4 and 5 hurricanes in the Atlantic basin has increased substantially since the early 1980s compared to the historical record that dates back to the mid-1880s (Ch. 2: Our Changing Climate, Key Message 8). This can be attributed to both natural variability and climate change.

Temperatures across the Southeast and Caribbean are expected to increase during this century, with shorter-term (year-to-year and decade-to-decade) fluctuations over time due to natural climate variability (Ch. 2: Our Changing Climate, Key Message 3).[4] Major consequences of warming include significant increases in the number of hot days (95°F or above) and decreases in freezing events. Although projected increases for some parts of the region by the year 2100 are generally smaller than for other regions of the United States, projected increases for interior states of the region are larger than coastal regions by 1°F to 2°F. Regional average increases are in the range of 4°F to 8°F (combined 25th to 75th percentile range for A2 and B1 emissions scenarios) and 2°F to 5°F for Puerto Rico.[11]

Southeast Temperature: Observed and Projected

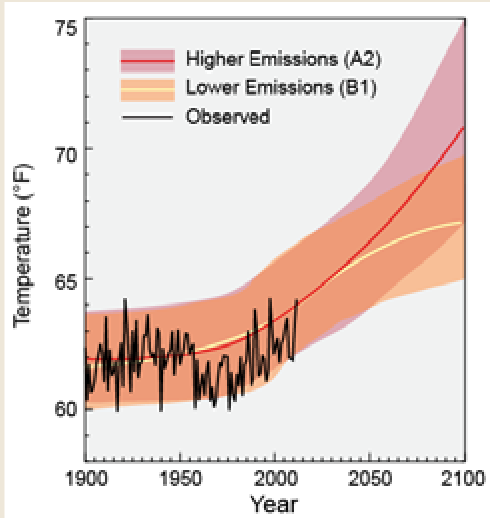

Figure 17.3. Observed annual average temperature for the Southeast and projected temperatures assuming substantial emissions reductions (lower emissions, B1) and assuming continued growth in emissions (higher emissions, A2).[11] For each emissions scenario, shading shows the range of projections and the line shows a central estimate. The projections were referenced to observed temperatures for the period 1901-1960. The region warmed during the early part of last century, cooled for a few decades, and is now warming again. The lack of an overall upward trend over the entire period of 1900-2012 is unusual compared to the rest of the U.S. and the globe. This feature has been dubbed the "warming hole" and has been the subject of considerable research, although a conclusive cause has not been identified. (Figure source: adapted from Kunkel et al. 2013[11]).

Projected Change in Number of Days Over 95°F

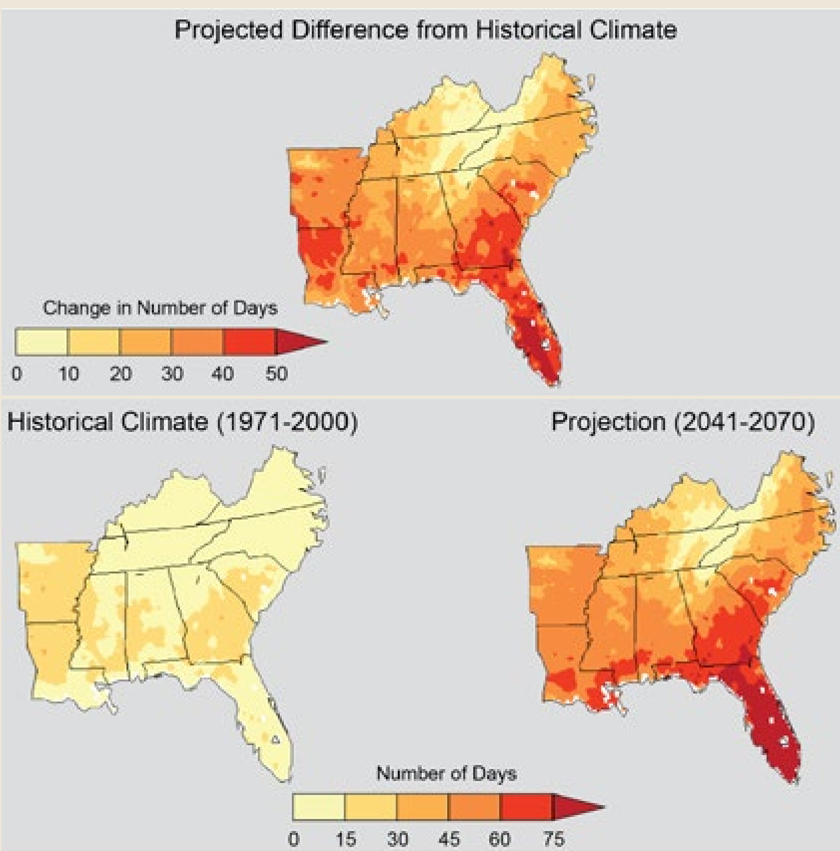

Figure 17.4. Projected average number of days per year with maximum temperatures above 95°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). Patterns are similar, but less pronounced, assuming a reduced emissions scenario (B1). (Figure source: NOAA NCDC / CICS-NC).

Projections of future precipitation patterns are less certain than projections for temperature increases.[11] Because the Southeast is located in the transition zone between projected wetter conditions to the north and drier conditions to the southwest, many of the model projections show only small changes relative to natural variations. However, many models do project drier conditions in the far southwest of the region and wetter conditions in the far northeast of the region, consistent with the larger continental-scale pattern of wetness and dryness (Ch. 2: Our Changing Climate, Key Message 5).[11] For the Caribbean, it is equally difficult to project the magnitude of precipitation changes, although the majority of models show future decreases in precipitation are likely, with a few areas showing increases. In general, annual average decreases are likely to be spread across the entire region.[4] Projections further suggest that warming will cause tropical storms to be fewer in number globally, but stronger in force, with more Category 4 and 5 storms (Ch. 2: Our Changing Climate, Key Message 8).[13] On top of the large increases in extreme precipitation observed during last century and early this century (Ch. 2: Our Changing Climate, Figures 2.16, 2.17, and 2.18), substantial further increases are projected as this century progresses (Ch. 2: Our Changing Climate, Figure 2.19).

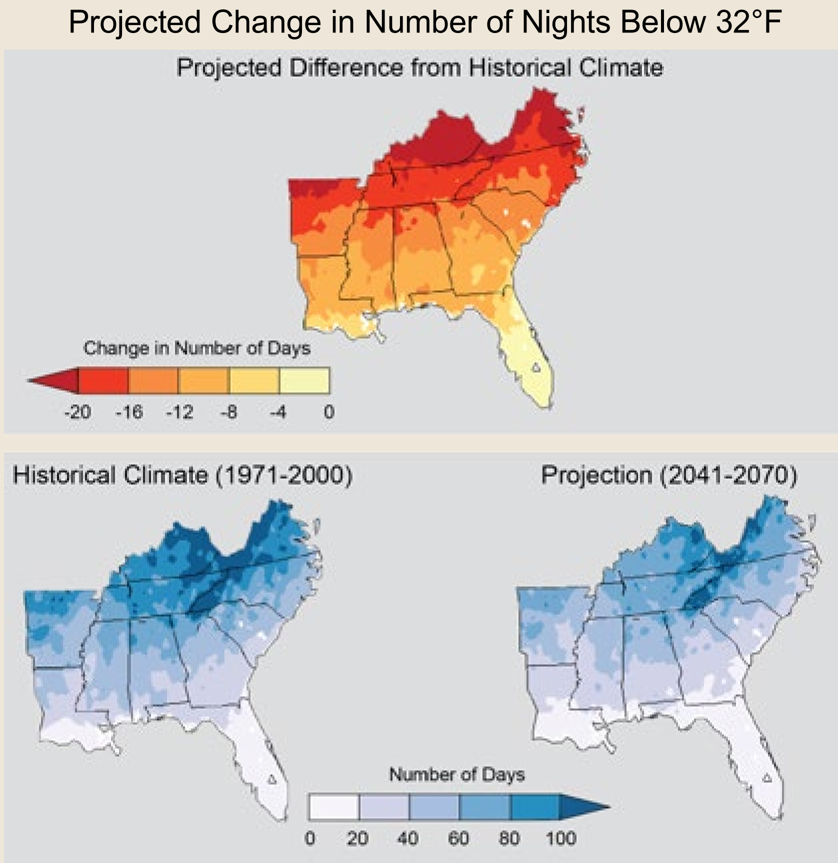

Figure 17.5. Projected average number of days per year with temperatures less than 32°F for 2041-2070 compared to 1971-2000, assuming emissions continue to grow (A2 scenario). Patterns are similar, but less pronounced, assuming a reduced emissions scenario (B1). (Figure source: NOAA NCDC / CICS-NC).

Key Message 1: Sea Level Rise Threats

Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.

Global sea level rise over the past century averaged approximately eight inches (Ch. 2: Our Changing Climate, Key Message 10),[14,15] and that rate is expected to accelerate through the end of this century.[16] Portions of the Southeast and Caribbean are highly vulnerable to sea level rise.[4,5] How much sea level rise is experienced in any particular place depends on whether and how much the local land is sinking (also called subsidence) or rising, and changes in offshore currents.[16,17]

Large numbers of cities, roads, railways, ports, airports, oil and gas facilities, and water supplies are at low elevations and potentially vulnerable to the impacts of sea level rise. New Orleans (with roughly half of its population living below sea level[19]), Miami, Tampa, Charleston, and Virginia Beach are among those most at risk.[20] As a result of current sea level rise, the coastline of Puerto Rico around Rincón is being eroded at a rate of 3.3 feet per year.[4]

According to a recent study co-sponsored by a regional utility, coastal counties and parishes in Alabama, Mississippi, Louisiana, and Texas, with a population of approximately 12 million, assets of about $2 trillion, and producers of $634 billion in annual gross domestic product, already face significant losses that annually average $14 billion from hurricane winds, land subsidence, and sea level rise. Future losses for the 2030 timeframe could reach $18 billion (with no sea level rise or change in hurricane wind speed) to $23 billion (with a nearly 3% increase in hurricane wind speed and just under 6 inches of sea level rise). Approximately 50% of the increase in the estimated losses is related to climate change. The study identified $7 billion in cost-effective adaptation investments that could reduce estimated annual losses by about 30% in the 2030 timeframe.[21]

The North Carolina Department of Transportation is raising the roadbed of U.S. Highway 64 across the Albemarle-Pamlico Peninsula by four feet, which includes 18 inches to allow for high-

Vulnerability to Sea Level Rise

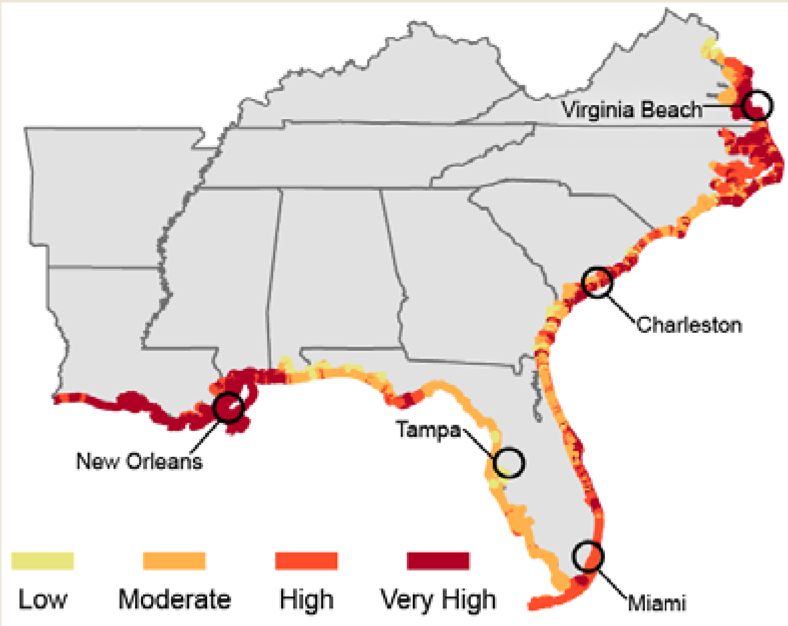

Figure 17.6. The map shows the relative risk that physical changes will occur as sea level rises. The Coastal Vulnerability Index used here is calculated based on tidal range, wave height, coastal slope, shoreline change, landform and processes, and historical rate of relative sea level rise. The approach combines a coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and yields a relative measure of the system's natural vulnerability to the effects of sea level rise. (Data from Hammar-Klose and Thieler 2001[18]).

er future sea levels.[22] Louisiana State Highway 1, heavily used for delivering critical oil and gas resources from Port Fourchon, is literally sinking, resulting in more frequent and more severe flooding during high tides and storms.[8] The Department of Homeland Security estimated that a 90-day shutdown of this road would cost the nation $7.8 billion.[23]

Sea level rise increases pressure on utilities – such as water and energy – by contaminating potential freshwater supplies with saltwater. Such problems are amplified during extreme dry periods with little runoff. Uncertainties in the scale, timing, and location of climate change impacts can make decision-making difficult, but response strategies, especially those that try to anticipate possible unintended consequences, can be more effective with early planning. Some utilities in the region are already taking sea level rise into account in the construction of new facilities and are seeking to diversify their water sources.[24]

There is an imminent threat of increased inland flooding during heavy rain events in low-lying coastal areas such as southeast Florida, where just inches of sea level rise will impair the capacity of stormwater drainage systems to empty into the ocean.[24] Drainage problems are already being experienced in many locations during seasonal high tides, heavy rains, and storm surge events. Adaptation options that are being assessed in this region include the redesign and improvement of storm drainage canals, flood control structures, and stormwater pumps.

As temperatures and sea levels increase, changes in marine and coastal systems are expected to affect the potential for energy resource development in coastal zones and the outer continental shelf. Oil and gas production infrastructure in bays and coves that are protected by barrier islands, for example, are likely to become increasingly vulnerable to storm surge as sea level rises and barrier islands deteriorate along the central Gulf Coast. The capacity for expanding and maintaining onshore and offshore support facilities and transportation networks is also apt to be affected.[25]

Sea level rise and storm surge can have impacts far beyond the area directly affected. Homes and infrastructure in low areas are increasingly prone to flooding during tropical storms. As a result, insurance costs may increase or coverage may become unavailable[26] and people may move from vulnerable areas, stressing the social and infrastructural capacity of surrounding areas. This migration also happens in response to extreme events such as Hurricane Katrina, when more than 200,000 migrants were temporarily housed in Houston and 42% indicated they would try to remain there (Ch. 9: Human Health, Figure 9.10).[27]

Homes and infrastructure in low-lying areas are increasingly vulnerable to flooding due to storm surge as sea level rises.

Highway 1 to Port Fourchon: Vulnerability of a Critical Link for U.S. Oil

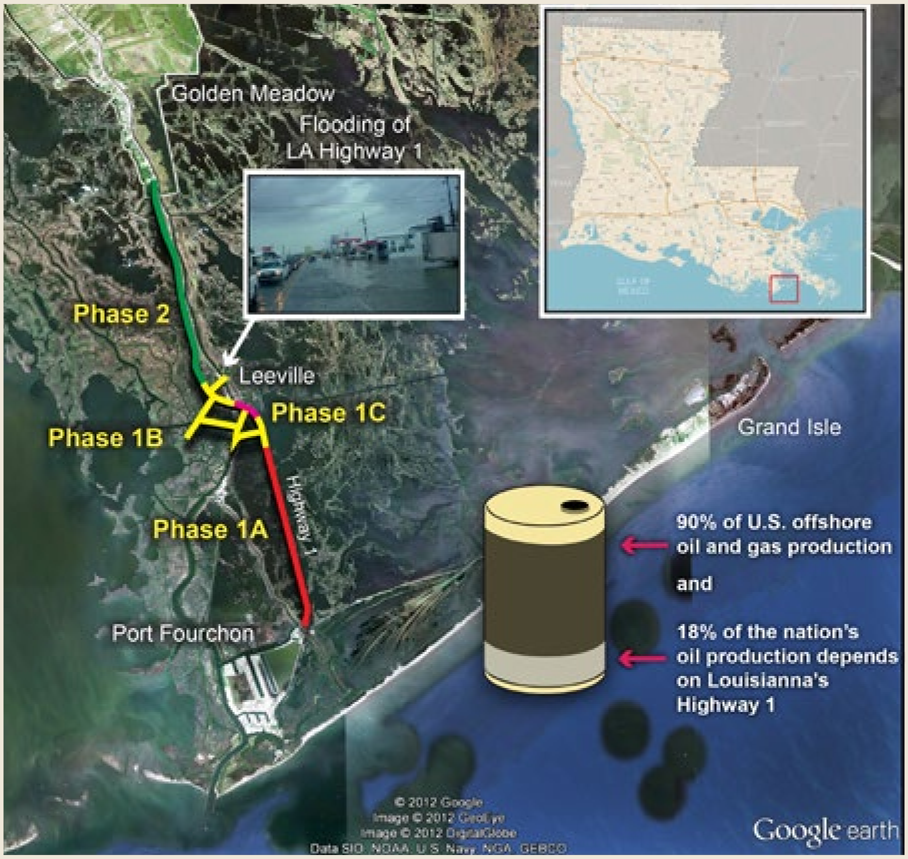

Figure 17.7. Highway 1 in southern Louisiana is the only road to Port Fourchon, whose infrastructure supports 18% of the nation's oil and 90% of the nation's offshore oil and gas production. Flooding is becoming more common on Highway 1 in Leeville (inset photo from flooding in 2004), on the way to Port Fourchon. See also Ch. 25: Coasts, Figure 25.5. (Figure and photo sources: Louisiana Department of Transportation and Development; State of Louisiana 2012[8]).

Reduction of wetlands also increases the potential for losses of important fishery habitat. Additionally, ocean warming could support shifts in local species composition, invasive or new locally viable species, changes in species growth rates, shifts in migratory patterns or dates, and alterations to spawning seasons.[4,31] Any of these could affect the local or regional seafood output and thus the local economy.

In some southeastern coastal areas, changes in salinity and water levels due to a number of complex interactions (including subsidence, availability of sediment, precipitation, and sea level rise) can happen so fast that local vegetation cannot adapt quickly enough and those areas become open water.[32] Fire, hurricanes, and other disturbances have similar effects, causing ecosystems to cross thresholds at which dramatic changes occur over short time frames.[33]

The impacts of sea level rise on agriculture derive from decreased freshwater availability, land loss, and saltwater intrusion. Saltwater intrusion is projected to reduce the availability of fresh surface and groundwater for irrigation, thereby limiting crop production in some areas.[34] Agricultural areas around Miami-Dade County and southern Louisiana with shallow groundwater tables are at risk of increased inundation and future loss of cropland with a projected loss of 37,500 acres in Florida with a 27-inch sea level rise,[35] which is well within the 1- to 4-foot range of sea level rise projected by 2100 (Ch. 2: Our Changing Climate, Key Message 10).

Furthermore, because income is a key indicator of climate vulnerability, people that have limited economic resources are more likely to be adversely affected by climate change impacts such as sea level rise. In the Gulf region, nearly 100% of the "most socially vulnerable people live in areas unlikely to be protected from inundation," bringing equity issues and environmental justice into coastal planning efforts.[28]

Ecosystems of the Southeast and Caribbean are exposed to and at risk from sea level rise, especially tidal marshes and swamps. Some tidal freshwater forests are already retreating, while mangrove forests (adapted to coastal conditions) are expanding landward.[29] The pace of sea level rise will increasingly lead to inundation of coastal wetlands in the region. Such a crisis in land loss has occurred in coastal Louisiana for several decades, with 1,880 square miles having been lost since the 1930s as a result of natural and man-made factors.[8,30] With tidal wetland loss, protection of coastal lands and people against storm surge will be compromised.

There are basically three types of adaptation options to rising sea levels: protect (such as building levees or other "hard" methods), accommodate (such as raising structures or using "soft" or natural protection measures such as wetlands restoration), and retreat.[15,32] Individuals and communities are using all of these strategies. However, regional cooperation among local, state, and federal governments can greatly improve the success of adapting to impacts of climate change and sea level rise. An excellent example is the Southeast Florida Regional Compact. Through collaboration of county, state, and federal agencies, a comprehensive action plan was developed that includes hundreds of actions and special Adaptation Action Areas.[37]

South Florida: Uniquely Vulnerable to Sea Level Rise

Figure 17.8. Sea level rise presents major challenges to South Florida's existing coastal water management system due to a combination of increasingly urbanized areas, aging flood control facilities, flat topography, and porous limestone aquifers. For instance, South Florida's freshwater well field protection areas (left map: pink areas) lie close to the current interface between saltwater and freshwater (red line), which will shift inland with rising sea level, affecting water managers' ability to draw drinking water from current resources. Coastal water control structures (right map: yellow circles) that were originally built about 60 years ago at the ends of drainage canals to keep saltwater out and to provide flood protection to urbanized areas along the coast are now threatened by sea level rise. Even today, residents in some areas such as Miami Beach are experiencing seawater flooding their streets (lower photo). (Maps from The South Florida Water Management District.[36] Photo credit: Luis Espinoza, Miami-Dade County Department of Regulatory and Economic Resources).

Key Message 2: Increasing Temperatures

Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

The negative effects of heat on human cardiovascular, cerebral, and respiratory systems are well established (Ch. 9: Human Health)(for example: Kovats and Hajat 2008; O'Neill and Ebi 2009[38]). Atlanta, Miami, New Orleans, and Tampa have already had increases in the number of days with temperatures exceeding 95°F, during which the number of deaths is above average.[39] Higher temperatures also contribute to the formation of harmful air pollutants and allergens.[40] Ground-level ozone is projected to increase in the 19 largest urban areas of the Southeast, leading to an increase in deaths.[41] A rise in hospital admissions due to respiratory illnesses, emergency room visits for asthma, and lost school days is expected.[42]

The climate in many parts of the Southeast and Caribbean is suitable for mosquitoes carrying malaria and yellow and dengue fevers. The small island states in the Caribbean already have a high health burden from climate-sensitive disease, including vector-borne and zoonotic (animal to human) diseases.[43] It is still uncertain how regional climate changes will affect vector-borne and zoonotic disease transmissions. While higher temperatures are likely to shorten both development and incubation time,[44] vectors (like disease-carrying insects) also need

Local Planning

Figure 17.9. Miami-Dade County staff leading workshop on incorporating climate change considerations in local planning. (Photo credit: Armando Rodriguez, Miami-Dade County).

Ground-level Ozone

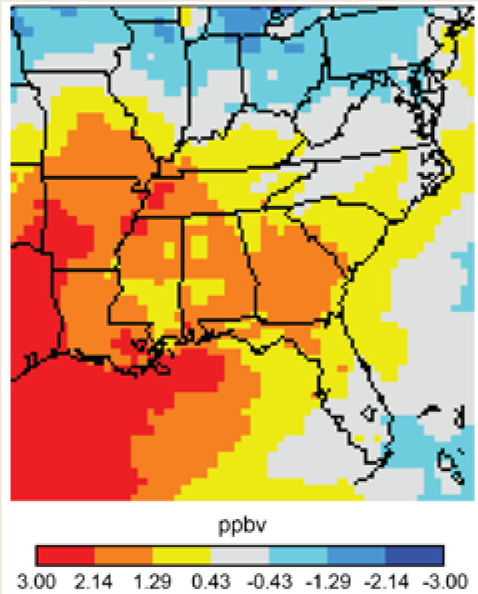

Figure 17.10. Ground-level ozone is an air pollutant that is harmful to human health and which generally increases with rising temperatures. The map shows projected changes in average annual ground level ozone pollution concentration in 2050 as compared to 2001, using a mid-range emissions scenario (A1B, which assumes gradual reductions from current emissions trends beginning around mid-century). (Figure source: adapted from Tagaris et al. 2009[42]).

the right conditions for breeding (water), for dispersal (vegetation and humidity), and access to susceptible vertebrate hosts to complete the disease transmission cycle.[5] While these transmission cycles are complex, increasing temperatures have the potential to result in an expanded region with more favorable conditions for transmission of these diseases.[45,46]

Climate change is expected to increase harmful algal blooms and several disease-causing agents in inland and coastal waters, which were not previously problems in the region.[47,48,49] For instance, higher sea surface temperatures are associated with higher rates of ciguatera fish poisoning,[48,50] one of the most common hazards from algal blooms in the region.[51] The algae that causes this food-borne illness is moving northward, following increasing sea surface temperatures.[52] Certain species of bacteria (*Vibrio,* for example) that grow in warm coastal waters and are present in Gulf Coast shellfish can cause infections in humans. Infections are now frequently reported both earlier and later by one month than traditionally observed.[53]

Coral reefs in the Southeast and Caribbean, as well as worldwide, are susceptible to climate change, especially warming waters and ocean acidification, whose impacts are exacerbated when coupled with other stressors, including disease, runoff, over-exploitation, and invasive species.[4,5]

An expanding population and regional land-use changes have reduced land available for agriculture and forests faster in the Southeast than in any other region in the contiguous United States.[54] Climate change is also expected to change the unwanted spread and locations of some non-native plants, which will result in new management challenges.[55]

Heat stress adversely affects dairy and livestock production.[56] Optimal temperatures for milk production are between 40ºF and 75ºF, and additional heat stress could shift dairy production northward.[57] A 10% decline in livestock yield is projected across the Southeast with a 9ºF increase in temperatures (applied as an incremental uniform increase in temperature between 1990 and 2060), related mainly to warmer summers.[58]

Summer heat stress is projected to reduce crop productivity, especially when coupled with increased drought (Ch. 6: Agriculture). The 2007 drought cost the Georgia agriculture industry $339 million in crop losses,[59] and the 2002 drought cost the agricultural industry in North Carolina $398 million.[5] A 2.2ºF increase in temperature would likely reduce overall productivity for corn, soybeans, rice, cotton, and peanuts across the South – though rising CO_2 levels could partially offset these decreases based on a crop yield simulation model.[60] In Georgia, climate projections indicate corn yields could decline by 15% and wheat yields by 20% through 2020.[61] In addition, many fruit crops from long-lived trees and bushes require chilling periods and may need to be replaced in a warming climate.[60]

Adaptation for agriculture involves decisions at many scales, from infrastructure investments (like reservoirs) to management decisions (like cropping patterns).[62] Dominant adaptation strategies include altering local planting choices to better match new climate conditions[62] and developing heat-tolerant crop varieties and breeds of livestock.[5,57] Most critical for effective adaptation is the delivery of climate risk information to decision-makers at appropriate temporal and spatial scales[57,62] and a focus on cropping systems that increase water-use efficiency, shifts toward irrigation, and more precise control of irrigation delivery (see also Ch. 28: Adaptation, Table 28.6).[5,57]

The southeastern U.S. (data include Texas and Oklahoma, not Puerto Rico) leads the nation in number of wildfires, averaging 45,000 fires per year,[63] and this number continues to increase.[64,65] Increasing temperatures contribute to increased fire frequency, intensity, and size,[63] though at some level of fire frequency, increased fire frequency would lead to decreased fire intensity. Lightning is a frequent initiator of wildfires,[66] and the Southeast currently has the greatest frequency of lightning strikes of any region of the country.[67] Increasing temperatures and changing atmospheric patterns may affect the number of lightning strikes in the Southeast, which could influence air quality, direct injury, and wildfires. Drought often correlates with large wildfire events, as seen with the Okeefenokee (2007) and Florida fires (1998). The 1998 Florida fires led to losses of more than $600 million.[68] Wildfires also affect human health through reduced air quality and direct injuries.[68,69,70] Expanding population and associated land-use fragmentation will limit the application of prescribed burning, a useful adaptive strategy.[65] Growth management could enhance the ability to pursue future adaptive management of forest fuels.

Forest disturbances caused by insects and pathogens are altered by climate changes due to factors such as increased tree stress, shifting phenology, and altered insect and pathogen lifecycles.[71] Current knowledge provides limited insights into specific impacts on epidemics, associated tree growth and mortality, and economic loss in the Southeast, though the overall extent and virulence of some insects and pathogens have been on the rise (for example, Hemlock Woolly Adelgid in the Southern Appalachians), while recent declines in southern pine beetle (*Dendroctonus frontalis* Zimmerman) epidemics in Louisiana and East Texas have been attributed to rising temperatures.[72] Due to southern forests' vast size and the high cost of management options, adaptation strategies are limited, except through post-epidemic management responses – for example, sanitation cuts and species replacement.

The Southeast has the existing power plant capacity to produce 32% of the nation's electricity.[73] Energy use is approximately 27% of the U.S. total, more than any other region.[5] Net energy demand is projected to increase, largely due to higher temperatures and increased use of air conditioning. This will potentially stress electricity generating capacity, distribution infrastructure, and energy costs. Energy costs are of particular concern for lower income households, the elderly, and other vulnerable communities, such as native tribes.[5,10] Long periods of extreme heat could also damage roadways by softening asphalt and cause deformities of railroad tracks, bridge joints, and other transportation infrastructure.[74]

Increasing temperatures will affect many facets of life in the Southeast and Caribbean region. For each impact there could be many possible responses. Many adaptation responses are described in other chapters in this document. For examples, please see the sector chapter of interest and Ch. 28: Adaptation.

Key Message 3: Water Availability

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.

Water resources in the Southeast are abundant and support heavily populated urban areas, rural communities, unique ecosystems, and economies based on agriculture, energy, and tourism. The region also experiences extensive droughts, such as the 2007 drought in Atlanta, Georgia, that created water conflicts among three states.[11,75] In northwestern Puerto Rico, water was rationed for more than 200,000 people during the winter and spring of 1997-1998 because of low reservoir levels.[76] Droughts are one of the most frequent climate hazards in the Caribbean, resulting in economic losses.[77] Water supply and demand in the Southeast and Caribbean are influenced by many changing factors, including climate (for example, temperature increases that contribute to increased transpiration from plants and evaporation from soils and water bodies), population, and land use.[4,5] While change in projected precipitation for this region has high uncertainty (Ch. 2: Our Changing Climate), there is still a reasonable expectation that there will be reduced water availability due to the increased evaporative losses resulting from rising temperatures alone.

With projected increases in population, the conversion of rural areas, forestlands, and wetlands into residential, commercial, industrial, and agricultural zones is expected to intensify.[54] The continued development of urbanized areas will increase water demand, exacerbate saltwater intrusion into freshwater aquifers, and threaten environmentally sensitive wetlands bordering urban areas.[24]

Additionally, higher sea levels will accelerate saltwater intrusion into freshwater supplies from rivers, streams, and groundwater sources near the coast. The region's aquaculture industry also may be compromised by climate-related stresses on groundwater quality and quantity.[78] Porous aquifers in some areas make them particularly vulnerable to saltwater intrusion.[36,79] For example, officials in the city of Hallandale Beach, Florida, have already abandoned six of their eight drinking water wells.[80]

With increasing demand for food and rising food prices, irrigated agriculture will expand in some states. Also, population expansion in the region is expected to increase domestic water demand. Such increases in water demand by the energy, agricultural, and urban sectors will increase the competition for water, particularly in situations where environmental water needs conflict with other uses.[5]

As seen from Figure 17.11, the net water supply availability in the Southeast is expected to decline over the next several decades, particularly in the western part of the region.[82] Analysis of current and future water resources in the Caribbean shows

Trends in Water Availability

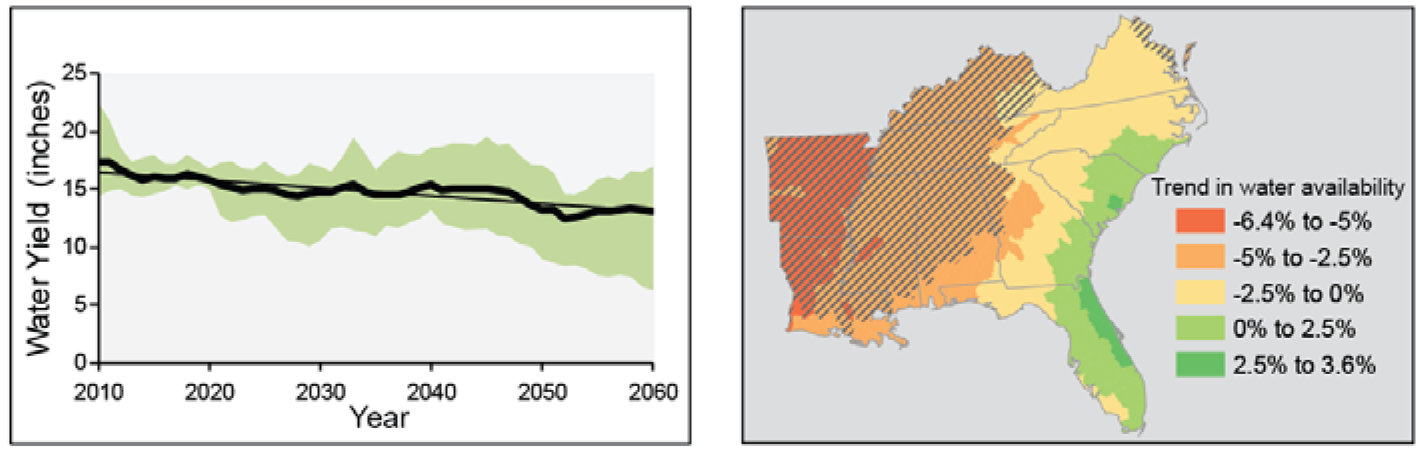

Figure 17.11. Left: Projected trend in Southeast-wide annual water yield (equivalent to water availability) due to climate change. The green area represents the range in predicted water yield from four climate model projections based on the A1B and B2 emissions scenarios. Right: Spatial pattern of change in water yield for 2010-2060 (decadal trend relative to 2010). The hatched areas are those where the predicted negative trend in water availability associated with the range of climate scenarios is statistically significant (with 95% confidence). As shown on the map, the western part of the Southeast region is expected to see the largest reductions in water availability. (Figure source: adapted from Sun et al. 2013[82]).

many of the small islands would be exposed to severe water stress under all climate change scenarios.[83]

New freshwater well fields may have to be established inland to replenish water supply lost from existing wells closer to the ocean once they are compromised by saltwater intrusion. Programs to increase water-use efficiency, reuse of wastewater, and water storage capacity are options that can help alleviate water supply stress.

The Southeast and Caribbean, which has a disproportionate number of the fastest-growing metropolitan areas in the country and important economic sectors located in low-lying coastal areas, is particularly vulnerable to some of the expected impacts of climate change. The most severe and widespread impacts are likely to be associated with sea level rise and changes in temperature and precipitation, which ultimately affect water availability. Changes in land use and land cover, more rapid in the Southeast and Caribbean than most other areas of the country, often interact with and serve to amplify the effects of climate change on regional ecosystems.

A Southeast River Basin Under Stress

Figure 17.12. The Apalachicola-Chattahoochee-Flint River Basin in Georgia exemplifies a place where many water uses are in conflict, and future climate change is expected to exacerbate this conflict.[84] The basin drains 19,600 square miles in three states and supplies water for multiple, often competing, uses, including irrigation, drinking water and other municipal uses, power plant cooling, navigation, hydropower, recreation, and ecosystems. Under future climate change, this basin is likely to experience more severe water supply shortages, more frequent emptying of reservoirs, violation of environmental flow requirements (with possible impacts to fisheries at the mouth of the Apalachicola), less energy generation, and more competition for remaining water. Adaptation options include changes in reservoir storage and release procedures and possible phased expansion of reservoir capacity.[84,85] Additional adaptation options could include water conservation and demand management. (Figure source: Georgakakos et al. 2010[84]).

Water recycling

Because of Clayton County, Georgia's, innovative water recycling project during the 2007-2008 drought, they were able to maintain reservoirs at near capacity and an abundant supply of water while neighboring Lake Lanier, the water supply for Atlanta, was at record lows. Clayton County developed a series of constructed wetlands used to filter treated water that recharges groundwater and supplies surface reservoirs. They have also implemented efficiency and leak detection programs[81] (for additional specific information see the Clayton County Water Authority website at: http://www.ccwa.us/).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages
A central component of the process was the Southeast Regional Climate Assessment Workshop that was held on September 26-27, 2011, in Atlanta, with approximately 75 attendees. This workshop began the process leading to a foundational Technical Input Report (TIR). That 341-page foundational "Southeast Region Technical Report to the National Climate Assessment"[5] comprised 14 chapters from over 100 authors, including all levels of government, non-governmental organizations, and business.

The writing team held a 2-day meeting in April 2012 in Ft. Lauderdale, engaged in multiple teleconference and webinar technical discussions, which included careful review of the foundational TIR,[5] nearly 60 additional technical inputs provided by the public, and other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors, and targeted consultation with additional experts by the Southeast chapter writing team and lead author of each key message.

Key message #1 Traceable Account

Sea level rise poses widespread and continuing threats to both natural and built environments and to the regional economy.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report.[5] A total of 57 technical inputs on a wide range of southeast-relevant topics (including sea level rise) were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that the rate of sea level rise has increased is based on satellite altimetry data and direct measurements such as tide gauges (Ch. 2: Our Changing Climate, Key Message 10). Numerous peer-reviewed publications describe increasing hazards associated with sea level rise and storm surge, heat waves, and intense precipitation for the Southeast.[5] For sea level rise, the authors relied on the NCA Sea Level Change Scenario[16] and detailed discussion in the foundational TIR.[5]

Evidence that sea level rise is a threat to natural and human environments is documented in detail within the foundational TIR[5] and other technical inputs, as well as considerable peer-reviewed literature (for example, Campanella 2010).[19] Field studies document examples of areas that are being flooded more regularly, saltwater intrusion into fresh water wells,[80] and changes from fresh to saltwater in coastal ecosystems (for example, freshwater marshes) causing them to die,[32] and increases in vulnerability of many communities to coastal erosion. Economic impacts are seen in the cost to avoid flooded roads, buildings, and ports;[23] the need to drill new fresh water wells;[80] and the loss of coastal ecosystems and their storm surge protection.

New information and remaining uncertainties
Tremendous improvement has been made since the last Intergovernmental Panel on Climate Change evaluation of sea level rise in 2007,[86] with strong evidence of mass loss of Greenland icecap and glaciers worldwide (Ch. 2: Our Changing Climate). Improved analyses of tide gauges, coastal elevations, and circulation changes in offshore waters have also provided new information on accelerating rates of rise (Ch. 2: Our Changing Climate, Figure 2.26). These have been documented in the NCA Sea Level Change Scenario publication.[16]

Uncertainties in the rate of sea level rise through this century stems from a combination of large differences in projections among different climate models, natural climate variability, uncertainties in the melting of land-based glaciers and the Antarctic and Greenland ice sheets especially, and uncertainties about future rates of fossil fuel emissions. A further key uncertainty is the rate of vertical land movement at specific locations. The two factors – sea level rise and subsidence – when combined, increase the impact of global sea level rise in any specific area. A third area of uncertainty is where and what adaptive plans and actions are being undertaken to avoid flooding and associated impacts on people, communities, facilities, infrastructure, and ecosystems.

Assessment of confidence based on evidence
Sea level is expected to continue to rise for several centuries, even if greenhouse gas emissions are stabilized, due to the time it takes for the ocean to absorb heat energy from the atmosphere. Because sea levels determine the locations of human activities and

ecosystems along the coasts, increases in sea level and in the rate of rise will nearly certainly have substantial impacts on natural and human systems along the coastal area. What specific locations will be impacted under what specific levels of sea level rise needs to be determined location-by-location. However, given that many locations are already being affected by rising seas, more and more locations will be impacted as sea levels continue to rise. Confidence in this key message is therefore judged to be very high.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Increasing temperatures and the associated increase in frequency, intensity, and duration of extreme heat events will affect public health, natural and built environments, energy, agriculture, and forestry.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report.[5] Technical inputs (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe increasing hazards associated with heat events and rising temperatures for the Southeast. The authors of a report on the Southeast climate[11] worked closely with the region's state climatologists on both the climatology and projections for temperature and associated heat events. Evidence of rising temperatures and current impacts[38,39] is based on an extensive set of field measurements.

There is considerable evidence of the effects of high air temperatures across a wide range of natural and managed systems in the Southeast. Increased temperatures affect human health and hospital admissions.[38,40,42]

Rising water temperatures also increase risks of bacterial infection from eating Gulf Coast shellfish[53] and increase algal blooms that have negative human health effects.[47,48] There is also evidence that there will be an increase in favorable conditions for mosquitoes that carry diseases.[46] Higher temperatures are detrimental to natural and urban environments, through increased wildfires in natural areas and managed forests[63,64,65,70] and increased invasiveness of some non-native plants.[55] High temperatures also contribute to more roadway damage and deformities of transportation infrastructure such as railroad tracks and bridges (Ch. 5: Transportation).[74] In addition, high temperatures increase net energy demand and costs, placing more stress on electricity generating plants and distribution infrastructure.

Increasing temperatures in the Southeast cause more stresses on crop and livestock agricultural systems. Heat stress reduces dairy and livestock production[56] and also reduces yields of various crops grown in this region (corn, soybean, peanuts, rice, and cotton).[60,61]

New information and remaining uncertainties

Since 2007, studies on impacts of higher temperatures have increased in many areas. Most of the publications cited above concluded that increasing temperatures in the Southeast will result in negative impacts on human health, the natural and built environments, energy, agriculture, and forestry.

A key issue (uncertainty) is the detailed mechanistic responses, including adaptive capacities and/or resilience, of natural and built environments, the public health system, energy systems, agriculture, and forests to increasing temperatures and extreme heat events.

Another uncertainty is how combinations of stresses, for example lack of water in addition to extreme heat, will affect outcomes. There is a need for more monitoring to document the extent and location of vulnerable areas (natural and human), and then research to assess how those impacts will affect productivity of key food and forest resources and human well-being. There is also a need for research that develops or identifies more resilient, adapted systems.

Assessment of confidence based on evidence

Increasing Temperatures: There is **high** confidence in documentation that projects increases in air temperatures (but not in the precise amount) and associated increases in the frequency, intensity, and duration of extreme heat events. Projections for increases in temperature are more certain in the Southeast than projections of changes in precipitation.

Impacts of increasing temperatures: Rising temperatures and the substantial increase in duration of high temperatures (for either the low [B1] or high [A2] emissions scenarios) above critical thresholds will have significant impacts on the population, agricultural industries, and ecosystems in the region. There is **high** confidence in documentation that increases in temperature in the Southeast will result in higher risks of negative impacts on human health, agricultural, and forest production; on natural systems; on the built environment; and on energy demand. There is **lower** confidence in the magnitude of these impacts, partly due to lack of information on how these systems will adapt (without human intervention) or be adapted (by people) to higher temperatures, and partly due to the limited knowledge base on the wide diversity that exists across this region in climates and human and natural systems.

Key message #3 Traceable Account

Decreased water availability, exacerbated by population growth and land-use change, will continue to increase competition for water and affect the region's economy and unique ecosystems.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Southeast Technical Input Report (TIR).[5] Technical inputs (57) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Chapter 2, Our Changing Climate, describes evidence for drought and precipitation in its key messages. Numerous salient studies support the key message of decreased water availability, as summarized for the Southeast in the TIR.[5]

Evidence for the impacts on the region's economy and unique ecosystems is also detailed in the TIR[5] and the broader literature surveyed by the authors.[77]

New information and remaining uncertainties

Many studies have been published since 2007 documenting increasing demands for water in the Southeast due to increases in populations and irrigated agriculture, in addition to water shortages due to extensive droughts.[5,11] There is also new evidence of losses in fresh water wells near coastlines due to saltwater intrusion[79,80] and of continuing conflicts among states for water use, particularly during drought periods.[5,84]

It is a virtual certainty that population growth in the Southeast will continue in the future and will be accompanied by a significant change in patterns of land use, which is projected to include a larger fraction of urbanized areas, reduced agricultural areas, and reduced forest cover.[54] With increasing population and human demand, competition for water among the agriculture, urban, and environment sectors is projected to continue to increase. However, the projected population increases for the lower (B1) versus higher (A2) emissions scenarios differ significantly (33% versus 151%).[11] Consequently, the effect of climate change on urban water demand for the lower emissions scenario is projected to be much lower than for that of the higher emissions scenario. Land-use change will also alter the regional hydrology significantly. Unless measures are adopted to increase water storage, availability of freshwater during dry periods will decrease, partly due to drainage and other human activities.

Projected increase in temperature will increase evaporation, and in areas (the western part of the region[87]) where precipitation is projected to decrease in response to climate change, the net amount of water supply for human and environmental uses may decrease significantly.

Along the coastline of the Southeast, accelerated intrusion of saltwater due to sea level rise will impact both freshwater well fields and potentially freshwater intakes in rivers and streams connected to the ocean. Although sea level rise (SLR) corresponding to the higher emissions scenario is much higher (twice as much), even the SLR for the lower emissions scenario will increasingly impact water supply availability in low-lying areas of the region, as these areas are already being impacted by SLR and land subsidence.

Projections of specific spatial and temporal changes in precipitation in the Southeast remain highly uncertain and it is important to know with a reasonable confidence the sign and the magnitude of this change in various parts of the large Southeast region.

For the Southeast, there are no reliable projections of evapotranspiration, another major factor that determines water yield. This adds to uncertainty about water availability.

There are inadequate regional studies at basin scales to determine the future competition for water supply among sectors (urban, agriculture, and environment).

There is a need for more accurate information on future changes in drought magnitude and frequency.

Assessment of confidence based on evidence

There is **high** confidence in each aspect of the key message: it is virtually certain that the water demand for human consumption in the Southeast will increase as a result of population growth. The past evidence of impacts during droughts and the projected changes in drivers (land-use change, population growth, and climate change) suggest that there is a **high** confidence of the above assessment of future water availability. However, without additional studies, the resilience and the adaptive capacity of the socioeconomic and environmental systems are not known.

Water supply is critical for sustainability of the region, particularly in view of increasing population and land-use changes. Climate models' precipitation projections are uncertain. Nonetheless, the combined effects of possible decreases in precipitation, increasing evaporation losses due to warming, and increasing demands for water due to higher populations (under either lower [B1] or higher [A2] emissions scenarios) will have a significant impact on water availability for all sectors.

Climate Change Impacts in the United States

CHAPTER 18
MIDWEST

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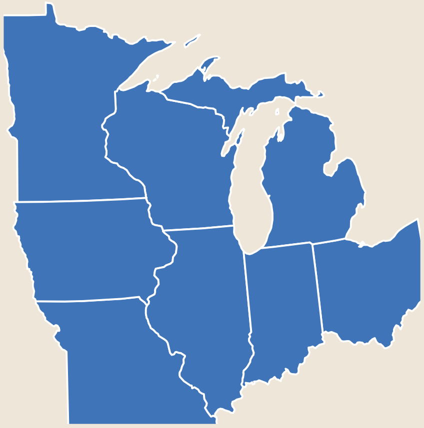

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

18 MIDWEST

Key Messages

1. **In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.**
2. **The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.**
3. **Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.**
4. **The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.**
5. **Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.**
6. **Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.**

The Midwest has a population of more than 61 million people (about 20% of the national total) and generates a regional gross domestic product of more than $2.6 trillion (about 19% of the national total).[1] The Midwest is home to expansive agricultural lands, forests in the north, the Great Lakes, substantial industrial activity, and major urban areas, including eight of the nation's 50 most populous cities. The region has experienced shifts in population, socioeconomic changes, air and water pollution, and landscape changes, and exhibits multiple vulnerabilities to both climate variability and climate change.

In general, climate change will tend to amplify existing climate-related risks from climate to people, ecosystems, and infrastructure in the Midwest (Ch. 10: Energy, Water, and Land). Direct effects of increased heat stress, flooding, drought, and late spring freezes on natural and managed ecosystems may be multiplied by changes in pests and disease prevalence, increased competition from non-native or opportunistic native species, ecosystem disturbances, land-use change, landscape fragmentation, atmospheric pollutants, and economic shocks such as crop failures or reduced yields due to extreme weather events. These added stresses, when taken collectively, are projected to alter the ecosystem and socioeconomic patterns and processes in ways that most people in the region would consider detrimental. Much of the region's fisheries, recreation, tourism, and commerce depend on the Great Lakes and expansive northern forests, which already face pollution and invasive species pressure that will be exacerbated by climate change.

Most of the region's population lives in cities, which are particularly vulnerable to climate change related flooding and life-threatening heat waves because of aging infrastructure and other factors. Climate change may also augment or intensify other stresses on vegetation encountered in urban environments, including increased atmospheric pollution, heat island effects, a highly variable water cycle, and frequent exposure to new pests and diseases. Some cities in the region are already engaged in the process of capacity building or are actively building resilience to the threats posed by climate change. The region's highly energy-intensive economy emits a disproportionately large amount of the gases responsible for warming

Temperatures are Rising in the Midwest

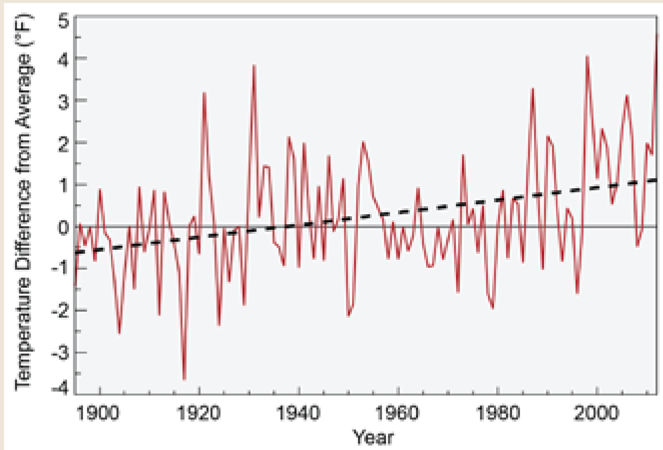

Figure 18.1. Annual average temperatures (red line) across the Midwest show a trend towards increasing temperature. The trend (dashed line) calculated over the period 1895-2012 is equal to an increase of 1.5°F. (Figure source: updated from Kunkel et al. 2013[4]).

the climate (called greenhouse gases or heat-trapping gases). But as discussed below, it also has a large and increasingly realized potential to reduce these emissions.

The rate of warming in the Midwest has markedly accelerated over the past few decades. Between 1900 and 2010, the average Midwest air temperature increased by more than 1.5°F (Figure 18.1). However, between 1950 and 2010, the average temperature increased twice as quickly, and between 1980 and 2010, it increased three times as quickly as it did from 1900 to 2010.[1] Warming has been more rapid at night and during winter. These trends are consistent with expectations of increased concentrations of heat-trapping gases and observed changes in concentrations of certain particles in the atmosphere.[1,2]

The amount of future warming will depend on changes in the atmospheric concentration of heat-trapping gases. Projections for regionally averaged temperature increases by the middle of the century (2046-2065) relative to 1979-2000 are approximately 3.8°F for a scenario with substantial emissions reductions (B1) and 4.9°F with continued growth in global emissions (A2). The projections for the end of the century (2081-2100) are approximately 5.6°F for the lower emissions scenario and 8.5°F for the higher emissions scenario (see Ch. 2: Our Changing Climate, Key Message 3).[3]

In 2011, 11 of the 14 U.S. weather-related disasters with damages of more than $1 billion affected the Midwest.[5] Several types of extreme weather events have already increased in frequency and/or intensity due to climate change, and further increases are projected (Ch. 2: Our Changing Climate, Key Message 7).[6]

Key Message 1: Impacts to Agriculture

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Agriculture dominates Midwest land use, with more than two-thirds of land designated as farmland.[3] The region accounts for about 65% of U.S. corn and soybean production,[7] mostly from non-irrigated lands.[1] Corn and soybeans constitute 85% of Midwest crop receipts, with high-value crops such as fruits and vegetables making up most of the remainder.[8] Corn and soybean yields increased markedly (by a factor of more than 5) over the last century largely due to technological innovation, but are still vulnerable to year-to-year variations in weather conditions.[9]

The Midwest growing season lengthened by almost two weeks since 1950, due in large part to earlier occurrence of the last spring freeze.[10] This trend is expected to continue,[3,11] though the potential agricultural consequences are complex and vary by crop. For corn, small long-term average temperature increases will shorten the duration of reproductive development, leading to yield declines,[12] even when offset by carbon dioxide (CO_2) stimulation.[13] For soybeans, yields have a two in three chance of increasing early in this century due to CO_2 fertilization, but these increases are projected to be offset later in the century by higher temperature stress[14] (see Figure 18.2 for projections of increases in the frost-free season length and the number of summer days with temperatures over 95°F).

Future crop yields will be more strongly influenced by anomalous weather events than by changes in average temperature or annual precipitation (Ch. 6: Agriculture). Cold injury due to a freeze event after plant budding can decimate fruit crop production,[15] as happened in 2002, and again in 2012, to Michigan's $60 million tart cherry crop. Springtime cold air outbreaks (at least two consecutive days during which the daily average surface air temperature is below 95% of the simulated average wintertime surface air temperature) are projected to continue to occur throughout this century.[16] As a result, increased productivity of some crops due to higher temperatures, longer growing seasons, and elevated CO_2 concentrations could be offset by increased freeze damage.[17] Heat waves during pol-

Projected Mid-Century Temperature Changes in the Midwest

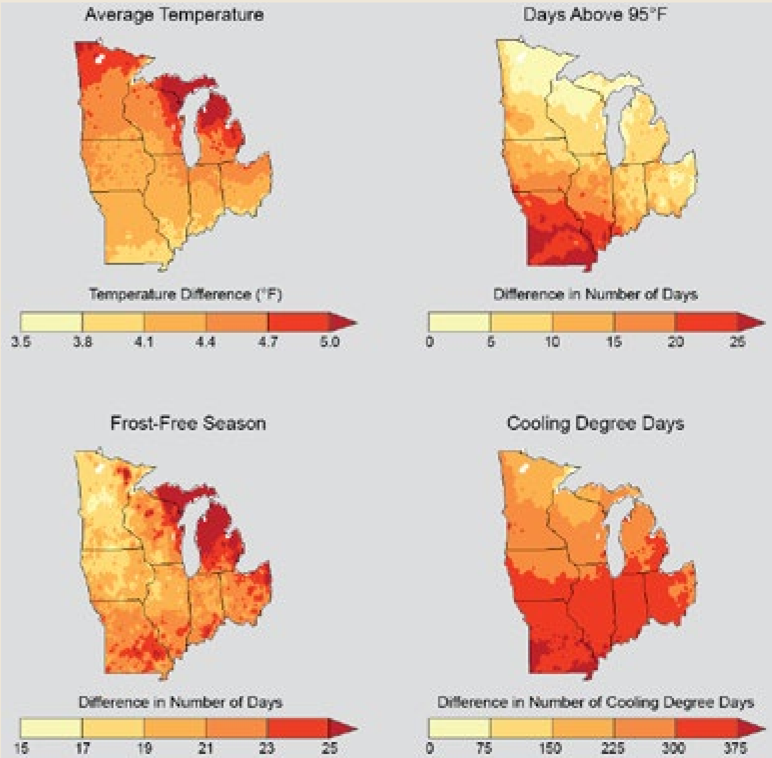

Figure 18.2. Projected increase in annual average temperatures (top left) by mid-century (2041-2070) as compared to the 1971-2000 period tell only part of the climate change story. Maps also show annual projected increases in the number of the hottest days (days over 95°F, top right), longer frost-free seasons (bottom left), and an increase in cooling degree days (bottom right), defined as the number of degrees that a day's average temperature is above 65°F, which generally leads to an increase in energy use for air conditioning. Projections are from global climate models that assume emissions of heat-trapping gases continue to rise (A2 scenario). (Figure source: NOAA NCDC / CICS-NC).

lination of field crops such as corn and soybean also reduce yields (Figure 18.3).[12] Wetter springs may reduce crop yields and profits,[18] especially if growers are forced to switch to late-planted, shorter-season varieties. A recent study suggests the volatility of U.S. corn prices is more sensitive to near-term climate change than to energy policy influences or to use of agricultural products for energy production, such as biofuel.[19]

Agriculture is responsible for about 8% of U.S. heat-trapping gas emissions,[20] and there is tremendous potential for farming practices to reduce emissions or store more carbon in soil.[21] Although large-scale agriculture in the Midwest historically led to decreased carbon in soils, higher crop residue inputs and adoption of different soil management techniques have reversed this trend. Other techniques, such as planting cover crops and no-till soil management, can further increase CO_2 uptake and reduce energy use.[22,23] Use of agricultural best management practices can also improve water quality by reducing the loss of sediments and nutrients from farm fields. Methane released from animals and their wastes can be reduced by altered diets and methane capture systems, and nitrous oxide production can be reduced by judicious fertilizer use[24] and improved waste handling.[21] In addition, if biofuel crops are grown sustainably,[25] they offer emissions reduction opportunities by substituting for fossil fuel-based energy (Ch. 10: Energy, Water, and Land).

Crop Yields Decline under Higher Temperatures

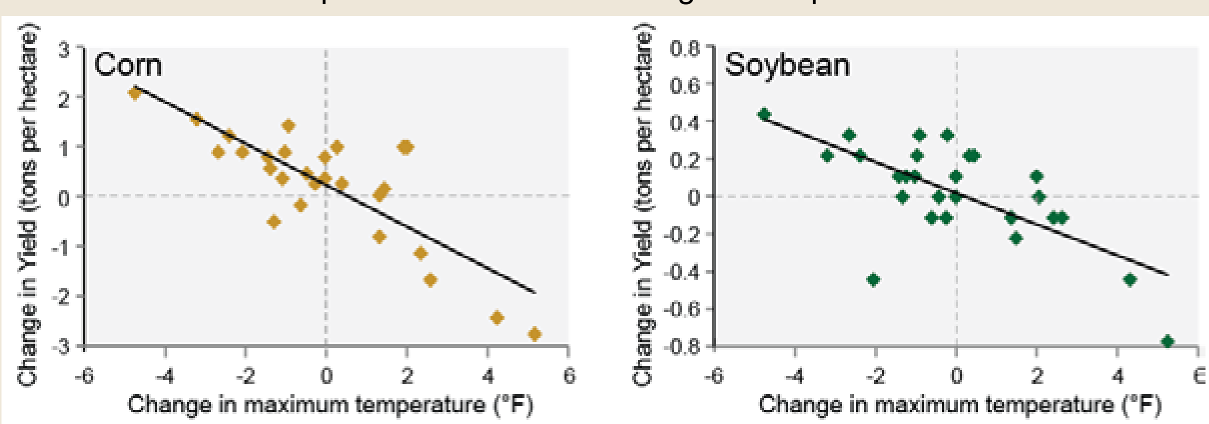

Figure 18.3. Crop yields are very sensitive to temperature and rainfall. They are especially sensitive to high temperatures during the pollination and grain filling period. For example, corn (left) and soybean (right) harvests in Illinois and Indiana, two major producers, were lower in years with average maximum summer (June, July, and August) temperatures higher than the average from 1980 to 2007. Most years with below-average yields are both warmer and drier than normal.[26,27] There is high correlation between warm and dry conditions during Midwest summers[28] due to similar meteorological conditions and drought-caused changes.[29] (Figure source: Mishra and Cherkauer 2010[26]).

Key Message 2: Forest Composition

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

The Midwest is characterized by a rich diversity of native species juxtaposed on one of the world's most productive agricultural systems.[30] The remnants of intact natural ecosystems in the region,[31] including prairies, forests, streams, and wetlands, are rich with varied species.[32] The combined effects of climate change, land-use change, and increasing numbers of invasive species are the primary threats to Midwest natural ecosystems.[33] Species most vulnerable to climate change include those that occur in isolated habitats; live near their physiological tolerance limits; have specific habitat requirements, low reproductive rates, or limited dispersal capability; are dependent on interactions with specific other species; and/or have low genetic variability.[34]

Among the varied ecosystems of the region, forest systems are particularly vulnerable to multiple stresses. The habitat ranges of many iconic tree species such as paper birch, quaking aspen, balsam fir, and black spruce are projected to decline substantially across the northern Midwest as they shift northward, while species that are common farther south, including several oaks and pines, expand their ranges northward into the region (Figure 18.4).[35,36] There is considerable variability in the likelihood of a species' habitat changing and the adaptability of the species with regard to climate change.[37] Migration to accommodate changed habitat is expected to be slow for many Midwest species, due to relatively flat topography, high latitudes, and fragmented habitats including the Great Lakes barrier. To reach areas that are 1.8°F cooler, species in mountainous terrains need to shift 550 feet higher in altitude (which can be achieved in only a few miles), whereas species in flat terrain like the Midwest must move as much as 90 miles north to reach a similarly cooler habitat.[38]

Although global forests currently capture and store more carbon each year than they emit,[39] the ability of forests to act as large, global carbon absorbers ("sinks") may be reduced by projected increased disturbances from insect outbreaks,[40] forest fire,[41] and drought,[42] leading to increases in tree mortality and carbon emissions. Some regions may even shift from being a carbon sink to being an atmospheric carbon dioxide source,[43,44] though large uncertainties exist, such as whether projected disturbances to forests will be chronic or episodic.[45] Midwest forests are more resilient to forest carbon losses than most western forests because of relatively high moisture availability, greater nitrogen deposition (which tends to act as a fertilizer), and lower wildfire risk.[43,46]

Forest Composition Shifts

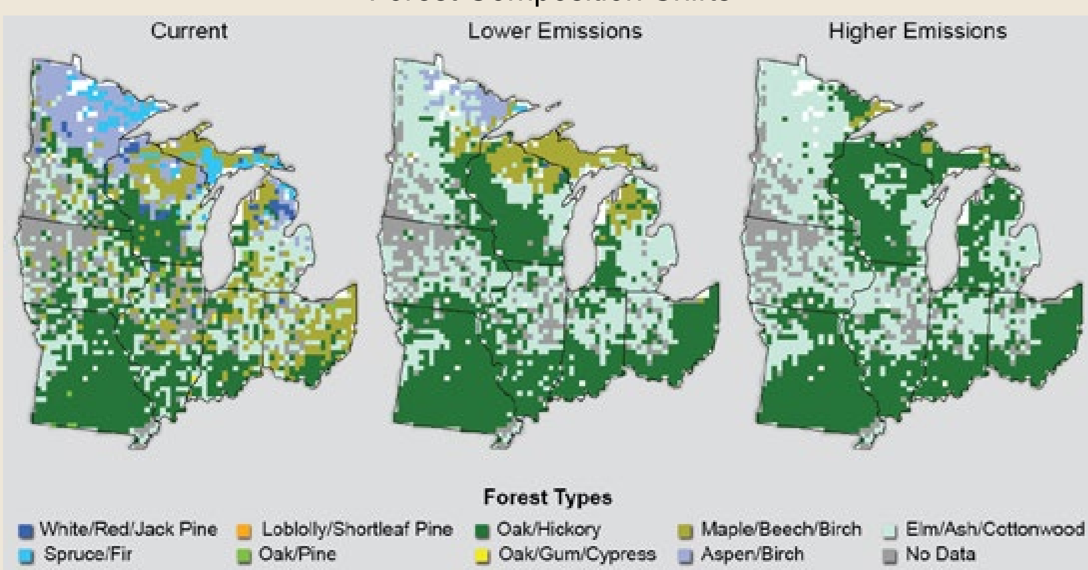

Figure 18.4. As climate changes, species can often adapt by changing their ranges. Maps show current and projected future distribution of habitats for forest types in the Midwest under two emissions scenarios, a lower scenario that assumes reductions in heat-trapping gas emissions (B1), and a very high scenario that assumes continued increases in emissions (A1FI). Habitats for white/red/jack pine, maple/beech/birch, spruce/fir, and aspen/birch forests are projected to greatly decline from the northern forests, especially under higher emissions scenarios, while various oak forest types are projected to expand.[37] While some forest types may not remain dominant, they will still be present in reduced quantities. Therefore, it is more appropriate to assess changes on an individual species basis, since all species within a forest type will not exhibit equal responses to climate change. (Figure source: Prasad et al. 2007[37]).

Key Message 3: Public Health Risks

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

The frequency of major heat waves in the Midwest has increased over the last six decades.[47] For the United States, mortality increases 4% during heat waves compared with non-heat wave days.[48] During July 2011, 132 million people across the U.S. were under a heat alert – and on July 20 of that year, the majority of the Midwest experienced temperatures in excess of 100°F. Heat stress is projected to increase as a result of both increased summer temperatures and humidity.[49,50] One study projected an increase of between 166 and 2,217 excess deaths per year from heat wave-related mortality in Chicago alone by 2081-2100.[51] The lower number assumes a climate scenario with significant reductions in emissions of greenhouse gases (B1), while the upper number assumes a scenario under which emissions continue to increase (A2). These projections are significant when compared to recent Chicago heat waves, where 114 people died from the heat wave of 1999 and about 700 died from the heat wave of 1995.[52] Heat response plans and early warning systems save lives, and from 1975 to 2004, mortality rates per heat event declined.[53] However, many municipalities lack such plans.[54]

More than 20 million people in the Midwest experience air quality that fails to meet national ambient air quality standards.[1] Degraded air quality due to human-induced emissions[55] and increased pollen season duration[56] are projected to be amplified with higher temperatures,[57] and pollution and pollen exposures, in addition to heat waves, can harm human health (Ch. 9: Human Health). Policy options exist (for example, see "Alternative Transportation Options Create Multiple Benefits") that could reduce emissions of both heat-trapping gases and other air pollutants, yielding benefits for human health and fitness. Increased temperatures and changes in precipitation patterns could also increase the vulnerability of Midwest residents to diseases carried by insects and rodents (Ch. 9: Human Health).[58]

Alternative transportation options create multiple benefits

The transportation sector produces one-third of U.S. greenhouse gas emissions, and automobile exhaust also contains precursors to fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3), which pose threats to public health. Adopting a low-carbon transportation system with fewer automobiles, therefore, could have immediate health "co-benefits" of both reducing climate change and improving human health via both improved air quality and physical fitness.

Reducing Emissions, Improving Health

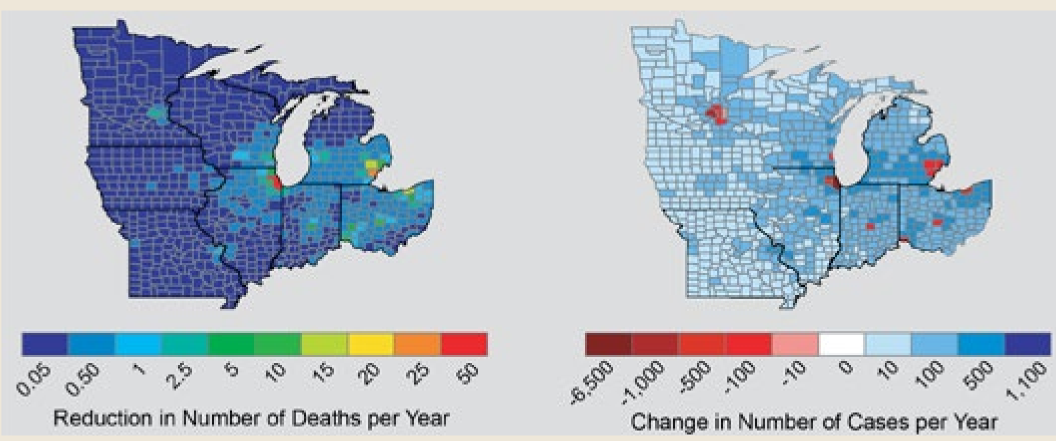

Figure 18.5. Annual reduction in the number of premature deaths (left) and annual change in the number of cases with acute respiratory symptoms (right) due to reductions in particulate matter and ozone caused by reducing automobile exhaust. The maps project health benefits if automobile trips shorter than five miles (round-trip) were eliminated for the 11 largest metropolitan areas in the Midwest. Making 50% of these trips by bicycle just during four summer months would save 1,295 lives and yield savings of more than $8 billion per year from improved air quality, avoided mortality, and reduced health care costs for the upper Midwest alone. (Figure source: Grabow et al. 2012; reproduced with permission from Environmental Health Perspectives[59]).

Key Message 4: Fossil-Fuel Dependent Electricity System

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

The Midwest is a major exporter of electricity to other U.S. regions and has a highly energy-intensive economy (Ch. 10: Energy, Water, and Land, Figure 10.4). Energy use per dollar of gross domestic product is approximately 20% above the national average, and per capita greenhouse gas emissions are 22% higher than the national average due, in part, to the reliance on fossil fuels, particularly coal for electricity generation.[1] A large range in seasonal air temperature causes energy demand for both heating and cooling, with the highest demand for winter heating. The demand for heating in major midwestern cities is typically five to seven times that for cooling,[1] although this is expected to shift as a result of longer summers, more frequent heat waves, and higher humidity, leading to an increase in the number of cooling degree days. This increased demand for cooling by the middle of this century is projected to exceed 10 gigawatts (equivalent to at least five large conventional power plants), requiring more than $6 billion in infrastructure investments.[60] Further, approximately 95% of the electrical generating infrastructure in the Midwest is susceptible to decreased efficiency due to higher temperatures.[60]

Climate change presents the Midwest's energy sector with a number of challenges, in part because of its current reliance on coal-based electricity[1] and an aging, less-reliable electric distribution grid[61] that will require significant reinvestment even without additional adaptations to climate change.[62]

Increased use of natural gas in the Midwest has the potential to reduce emissions of greenhouse gases. The Midwest also has potential to produce energy from zero- and low-carbon sources, given its wind, solar, and biomass resources, and potential for expanded nuclear power. The Midwest does not have the highest solar potential in the country (that is found in the Southwest), but its potential is nonetheless vast, with some parts of the Midwest having as good a solar resource as Florida.[63] More than one-quarter of national installed wind energy capacity, one-third of biodiesel capacity, and more than two-thirds of ethanol production are located in the Midwest (see also Ch. 4: Energy and Ch. 10: Energy, Water, and Land).[1] Progress toward increasing renewable energy is hampered by electricity prices that are distorted through a mix of direct and indirect subsidies and unaccounted-for costs for conventional energy sources.[64]

Key Message 5: Increased Rainfall and Flooding

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Precipitation in the Midwest is greatest in the east, declining towards the west. Precipitation occurs about once every seven days in the western part of the region and once every three days in the southeastern part.[65] The 10 rainiest days can contribute as much as 40% of total precipitation in a given year.[65] Generally, annual precipitation increased during the past century (by up to 20% in some locations), with much of the increase driven by intensification of the heaviest rainfalls.[65,66] This tendency towards more intense precipitation events is projected to continue in the future.[67]

Model projections for precipitation changes are less certain than those for temperature.[3,4] Under a higher emissions scenario (A2), global climate models (GCMs) project average winter and spring precipitation by late this century (2071-2099) to increase 10% to 20% relative to 1971-2000, while changes in summer and fall are not expected to be larger than natural variations. Projected changes in annual precipitation show increases larger than natural variations in the north and smaller in the south (Ch. 2: Our Changing Climate, Key Message 5).[4] Regional climate models (RCMs) using the same emissions scenario also project increased spring precipitation (9% in 2041-2062 relative to 1979-2000) and decreased summer precipitation (by an average of about 8% in 2041-2062 relative to 1979-2000) particularly in the southern portions of the Midwest.[3] Increases in the frequency and intensity of extreme precipitation are projected across the entire region in both GCM and RCM simulations (Figure 18.6), and these increases are generally larger than the projected changes in average precipitation.[3,4]

Flooding can affect the integrity and diversity of aquatic ecosystems. Flooding also causes major human and economic consequences by inundating urban and agricultural land and by disrupting navigation in the region's roads, rivers, and reservoirs (see Ch. 5: Transportation, Ch. 9: Human Health, and Ch. 11: Urban). For example, the 2008 flooding in the Midwest caused 24 deaths, $15 billion in losses via reduced agricultural yields, and closure of key transportation routes.[1] Water infrastructure for flood control, navigation, and other purposes is susceptible to climate change impacts and other forces because the de-

When it Rains, it Pours

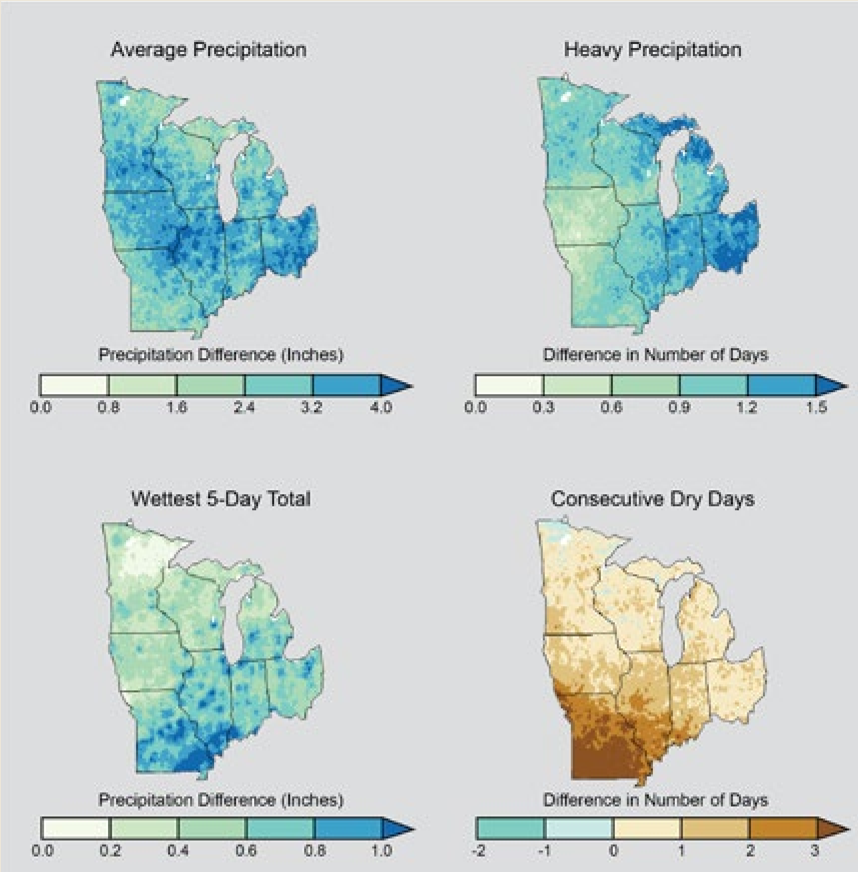

Figure 18.6. Precipitation patterns affect many aspects of life, from agriculture to urban storm drains. These maps show projected changes for the middle of the current century (2041-2070) relative to the end of the last century (1971-2000) across the Midwest under continued emissions (A2 scenario). Top left: the changes in total annual average precipitation. Across the entire Midwest, the total amount of water from rainfall and snowfall is projected to increase. Top right: increase in the number of days with very heavy precipitation (top 2% of all rainfalls each year). Bottom left: increases in the amount of rain falling in the wettest 5-day period over a year. Both (top right and bottom left) indicate that heavy precipitation events will increase in intensity in the future across the Midwest. Bottom right: change in the average maximum number of consecutive days each year with less than 0.01 inches of precipitation. An increase in this variable has been used to indicate an increase in the chance of drought in the future. (Figure source: NOAA NCDC / CICS-NC).

signs are based upon historical patterns of precipitation and streamflow, which are no longer appropriate guides.

Snowfall varies across the region, comprising less than 10% of total precipitation in the south, to more than half in the north, with as much as two inches of water available in the snowpack at the beginning of spring melt in the northern reaches of the river basins.[68] When this amount of snowmelt is combined with heavy rainfall, the resulting flooding can be widespread and catastrophic (see "Cedar Rapids: A Tale of Vulnerability and Response").[69] Historical observations indicate declines in the frequency of high magnitude snowfall years over much of the Midwest,[70] but an increase in lake effect snowfall.[71] These divergent trends and their inverse relationships with air temperatures make overall projections of regional impacts of the associated snowmelt extremely difficult. Large-scale flooding can also occur due to extreme precipitation in the absence of snowmelt (for example, Rush Creek and the Root River, Minnesota, in August 2007 and multiple rivers in southern Minnesota in September 2010).[72] These warm-season events are projected to increase in magnitude. Such events tend to be more regional and less likely to cover as large an area as those that occur in spring, in part because soil water storage capacity is typically much greater during the summer.

Changing land use and the expansion of urban areas are reducing water infiltration into the soil and increasing surface runoff. These changes exacerbate impacts caused by increased precipitation intensity. Many major Midwest cities are served by combined storm and sewage drainage systems. As surface area has been increasingly converted to impervious surfaces (such as asphalt) and extreme precipitation events have intensified, combined sewer overflow has degraded water quality, a phenomenon expected to continue to worsen with increased urbanization and climate change.[75] The U.S. Environmental Protection Agency (EPA) estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] The Great Lakes, which provide drinking water to more than 40 million people and are home to more than 500 beaches,[75] have been subject to recent sewage overflows. For example, stormwater across the city of Milwaukee recently showed high human fecal pathogen levels at all 45 outflow locations, indicating widespread sewage contamination.[77] One study estimated that increased storm events will lead to an increase of up to 120% in combined sewer overflows into Lake Michigan by 2100 under a very high emissions scenario (A1FI),[75] leading to additional human health issues and beach closures. Municipalities may be forced to invest in new infrastructure to protect human health and water quality in the Great Lakes, and local communities could face tourism losses from fouled nearshore regions.

Increased precipitation intensity also increases erosion, damaging ecosystems and increasing delivery of sediment and subsequent loss of reservoir storage capacity. Increased storm-induced agricultural runoff and rising water temperatures

Cedar Rapids: A Tale of Vulnerability and Response

Cedar Rapids, Des Moines, Iowa City, and Ames, Iowa, have all suffered multi-million-dollar losses from floods since 1993. In June 2008, a record flood event exceeded the once-in-500-year flood level by more than 5 feet, causing $5 to $6 billion in damages from flooding, or more than $40,000 per resident of the city of Cedar Rapids.[73] The flood inundated much of the downtown, damaging more than 4,000 structures, including 80% of government offices, and displacing 25,000 people.[74] The record flood at Cedar Rapids was the result of low reservoir capacity and extreme rainfall on soil already saturated from unusually wet conditions. Rainfall amounts comparable to those in 1993 (8 inches over two weeks) overwhelmed a flood control system designed largely for a once-in-100-year flood event. Such events are consistent with observations and projections of wetter springs and more intense precipitation events (see Figure 18.6). With the help of more than $3 billion in funding from the federal and state government, Cedar Rapids is recovering and has taken significant steps to reduce future flood damage, with buyouts of more than 1,000 properties, and numerous buildings adapted with flood protection measures.

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have increased non-point source pollution problems in recent years.[78] This has led to increased phosphorus and nitrogen loading, which in turn is contributing to more and prolonged occurrences of low-oxygen “dead zones” and to harmful, lengthy, and dense algae growth in the Great Lakes and other Midwest water bodies.[79] (Such zones and their causes are also discussed in Ch. 25: Coasts, Ch. 15: Biogeochemical Cycles, and Ch. 3: Water, Key Message 6). Watershed planning can be used to reduce water quantity and quality problems due to changing climate and land use.

While there was no apparent change in drought duration in the Midwest region as a whole over the past century,[80] the average number of days without precipitation is projected to increase in the future. This could lead to agricultural drought and suppressed crop yields.[9] This would also increase thermoelectric power plant cooling water temperatures and decrease cooling efficiency and plant capacity because of the need to avoid discharging excessively warm water (see also Ch. 4: Energy, and Ch. 10: Energy, Water, and Land).[60]

Key Message 6: Increased Risks to the Great Lakes

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

The Great Lakes, North America’s largest freshwater feature, have recently recorded higher water temperatures and less ice cover as a result of changes in regional climate (see also Ch. 2: Our Changing Climate, Key Message 11). Summer surface water temperatures in Lakes Huron increased 5.2°F and in Lake Ontario, 2.7°F, between 1968 and 2002,[81] with smaller increases in Lake Erie.[81,82] Due to the reduction in ice cover, the temperature of surface waters in Lake Superior during the summer increased 4.5°F, twice the rate of increase in air temperature.[83] These lake surface temperatures are projected to rise by as much as 7°F by 2050 and 12.1°F by 2100.[84,85] Higher temperatures, increases in precipitation, and lengthened growing seasons favor production of blue-green and toxic algae that can harm fish, water quality, habitats, and aesthetics,[79,84,86] and could heighten the impact of invasive species already present.[87]

In the Great Lakes, the average annual maximum ice coverage during 2003-2013 was less than 43% compared to the 1962-2013 average of 52%,[88] lower than any other decade during the period of measurements (Figure 18.7), although there is substantial variability from year to year. During the 1970s, which included several extremely cold winters, maximum ice coverage averaged 67%. Less ice, coupled with more frequent and intense storms (as indicated by some analyses of historical wind speeds),[89] leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.[84,90] Reduced ice cover also has the potential to lengthen the shipping season.[91] The navigation season increased by an average of eight days between 1994 and 2011, and the Welland Canal in the St. Lawrence River remained open nearly two weeks longer. Increased shipping days benefit commerce but could also increase shoreline scouring and bring in more invasive species.[91,92]

Changes in lake levels can also influence the amount of cargo that can be carried on ships. On average, a 1000-foot ship sinks into the water by one inch per 270 tons of cargo;[93] thus if a ship is currently limited by water depth, any lowering of lake levels will result in a proportional reduction in the amount of cargo that it can transport to Great Lakes ports. However, current estimates of lake level changes are uncertain, even for continued increases in global greenhouse gas emissions (A2 scenario). The most recent projections suggest a slight decrease or even a small rise in levels.[94] Recent studies have also indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[94,95,96,97] The recent studies, along with the large spread in existing modeling results, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty (see Appendix 3: Climate Science Supplemental Message 8).

Ice Cover in the Great Lakes

Figure 18.7. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963 through the winter of 1971-1972. The most recent period includes the eleven years from 2003 to 2013. (Data updated from Bai and Wang, 2012[88]).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
The assessment process for the Midwest Region began with a workshop was that was held July 25, 2011, in Ann Arbor, Michigan. Ten participants discussed the scope and authors for a foundational Technical Input Report (TIR) report entitled "Midwest Technical Input Report."[98] The report, which consisted of nearly 240 pages of text organized into 13 chapters, was assembled by 23 authors representing governmental agencies, non-governmental organizations (NGOs), tribes, and other entities.

The Chapter Author Team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[98] and of approximately 45 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team convened teleconferences and exchanged extensive emails to define the scope of the chapter for their expert deliberation of input materials and to generate the chapter text and figures. Each expert drafted key messages, initial text and figure drafts and traceable accounts that pertained to their individual fields of expertise. These materials were then extensively discussed by the team and were approved by the team members.

Key message #1 Traceable Account

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Description of evidence base
The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for altered growing seasons across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] and its references provide specific details for the Midwest. Evidence for longer growing seasons in the Midwest is based on regional temperature records and is incontrovertible, as is evidence for increasing carbon dioxide concentrations.

U.S. Department of Agriculture data tables provide evidence for the importance of the eight Midwest states for U.S. agricultural production.[8] Evidence for the effect of future elevated carbon dioxide concentrations on crop yields is based on scores of greenhouse and field experiments that show a strong fertilization response for C_3 plants such as soybeans and wheat and a positive but not as strong a response for C_4 plants such as corn. Observational data, evidence from field experiments, and quantitative modeling are the evidence base of the negative effects of extreme weather events on crop yield: early spring heat waves followed by normal frost events have been shown to decimate Midwest fruit crops; heat waves during flowering, pollination, and grain filling have been shown to significantly reduce corn and wheat yields; more variable and intense spring rainfall has delayed spring planting in some years and can be expected to increase erosion and runoff; and floods have led to crop losses.[12,13,14]

New information and remaining uncertainties
Key issues (uncertainties) are: a) the rate at which grain yield improvements will continue to occur, which could help to offset the overall negative effect of extreme events at least for grain crops (though not for individual farmers); and b) the degree to which genetic improvements could make some future crops more tolerant of extreme events such as drought and heat stress. Additional uncertainties are: c) the degree to which accelerated soil carbon loss will occur as a result of warmer winters and the resulting effects on soil fertility and soil water availability; and d) the potential for increased pest and disease pressure as southern pests such as soybean rust move northward and existing pests better survive milder Midwest winters.

Assessment of confidence based on evidence

Because nearly all studies published to date in the peer-reviewed literature agree that Midwest crops benefit from CO_2 fertilization and some benefit from a longer growing season, there is **very high** confidence in this component of the key message.

Studies also agree that full benefits of climate change will be offset partly or fully by more frequent heat waves, early spring thaws followed by freezing temperatures, more variable and intense rainfall events, and floods. Again, there is **very high** confidence in this aspect.

There is less certainty (**high**) about pest effects and about the potential for adaptation actions to significantly mitigate the risk of crop loss.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key Message #2 Traceable Account

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for increased temperatures and altered growing seasons across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Messages 3 and 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment,"[4] with its references, provides specific details for the Midwest. Evidence that species have been shifting northward or ascending in altitude has been mounting for numerous species, though less so for long-lived trees. Nearly all studies to date published in the peer-reviewed literature agree that many of the boreal species of the north will eventually retreat northward. The question is when. Multiple models and paleoecological evidence show these trends have occurred in the past and are projected to continue in the future.[36]

The forests of the eastern United States (including the Midwest) have been accumulating large quantities of carbon over the past century,[23] but evidence shows this trend is slowing in recent decades. There is a large amount of forest inventory data supporting the gradual decline in carbon accumulation throughout the eastern United States,[99] as well as evidence of increasing disturbances and disturbance agents that are reducing overall net productivity in many of the forests.

New information and remaining uncertainties

A key issue (uncertainty) is the rate of change of habitats and for organisms adapting or moving as habitats move. The key questions are: How much will the habitats change (what scenarios and model predictions will be most correct)? As primary habitats move north, which species will be able to keep up with changing habitats on their own or with human intervention through assisted migration, management of migration corridors, or construction or maintenance of protected habitats within species' current landscapes?

Viable avenues to improving the information base are determining which climate models exhibit the best ability to reproduce the historical and potential future change in habitats, and determining how, how fast, and how far various species can move or adapt.

An additional key source of uncertainty is whether projected disturbances to forests are chronic or episodic in nature.[45]

Assessment of confidence based on evidence

There is **very high** confidence in this key message, given the evidence base and remaining uncertainties.

Key Message #3 Traceable Account

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather such as heat waves across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 7) and its Traceable Accounts. Specific details for the Midwest are in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Heat waves: The occurrence of heat waves in the recent past has been well-documented,[1,15,49] as have health outcomes (particularly with regards to mortality). Projections of thermal regimes indicate increased frequency of periods with high air temperatures (and high apparent temperatures, which are a function of both air temperature and humidity). These projections are relatively robust and consistent between studies.

Humidity: Evidence on observed and projected increased humidity can be found in a recent study.[49]

Air quality: In 2008, in the region containing North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio, over 26 million people lived in counties that failed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (particles with diameter below 2.5 microns), and over 24 million lived in counties that failed the NAAQS for ozone (O_3).[1] Because not all counties have air quality measurement stations in place, these data must be considered a lower bound on the actual number of counties that violate the NAAQS. Given that the NAAQS were designed principally with the goal of protecting human health, failure to meet these standards implies a significant fraction of the population live in counties characterized by air quality that is harmful to human health. While only relatively few studies have sought to make detailed air quality projections for the future, those that have[1] generally indicate declining air quality (see uncertainties below).

Water quality: The EPA estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] Combined sewers are designed to capture both sanitary sewage and stormwater. Combined sewer overflows lead to discharge of untreated sewage as a result of precipitation events, and can threaten human health. While not all urban areas within the Midwest have combined sewers for delivery to wastewater treatment plants, many do (for example, Chicago and Milwaukee), and such systems are vulnerable to combined sewer overflows during extreme precipitation events. Given projected increases in the frequency and intensity of extreme precipitation events in the Midwest (Chapter 2: Our Changing Climate, Key Message 6),[75] it appears that sewer overflow will continue to constitute a significant current health threat and a critical source of climate change vulnerability for major urban areas within the Midwest.

New information and remaining uncertainties

Key issues (uncertainties) are: Human health outcomes are contingent on a large number of non-climate variables. For example, morbidity and mortality outcomes of extreme heat are strongly determined by a) housing stock and access to air-conditioning in residences; b) existence and efficacy of heat wave warning and response plans (for example, foreign-language-appropriate communications and transit plans to public cooling centers, especially for the elderly); and c) co-stressors (for example, air pollution). Further, heat stress is dictated by apparent temperature, which is a function of both air temperature and humidity. Urban heat islands tend to exacerbate elevated temperatures and are largely determined by urban land use and human-caused heat emissions. Urban heat island reduction plans (for example, planted green roofs) represent one ongoing intervention. Nevertheless, the occurrence of extreme heat indices will increase under all climate scenarios. Thus, in the absence of policies to reduce heat-related illness/death, these impacts will increase in the future.

Air quality is a complex function not only of physical meteorology but emissions of air pollutants and precursor species. However, since most chemical reactions are enhanced by warmer temperatures, as are many air pollutant emissions, warmer temperatures may lead to worsening of air quality, particularly with respect to tropospheric ozone (see Ch. 9: Human Health). Changes in humidity are more difficult to project but may amplify the increase in heat stress due to rising temperatures alone.[49]

Combined sewer overflow is a major threat to water quality in some midwestern cities now. The tendency towards increased magnitude of extreme rain events (documented in the historical record and projected to continue in downscaling analyses) will cause an increased risk of waterborne disease outbreaks in the absence of infrastructure overhaul. However, mitigation actions are available, and the changing structure of cities (for example, reducing impervious surfaces) may offset the impact of the changing climate.

Assessment of confidence based on evidence

In the absence of concerted efforts to reduce the threats posed by heat waves, increased humidity, degraded air quality and degraded water quality, climate change will increase the health risks associated with these phenomena. However, these projections are contingent on underlying assumptions regarding socioeconomic conditions and demographic trends in the region. Confidence is therefore **high** regarding this key message.

Key Message #4 Traceable Account

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The Midwest's disproportionately large reliance on coal for electricity generation and the energy intensity of its agricultural and manufacturing sectors are all well documented in both government and industry records, as is the Midwest's contribution to greenhouse gases.[1] The region's potential for zero- and lower-carbon energy production is also well documented by government and private assessments. Official and regular reporting by state agencies and non-governmental organizations demonstrates the Midwest's progress toward a decarbonized energy mix (Ch. 4: Energy; Ch. 10: Energy, Water, and Land).[1]

There is evidence that the Midwest is steadily decarbonizing its electricity generation through a combination of new state-level policies (for example, energy efficiency and renewable energy standards) and will continue to do so in response to low natural gas prices, falling prices for renewable electricity (for example, wind and solar), greater market demand for lower-carbon energy from consumers, and new EPA regulations governing new power plants. Several midwestern states have established Renewable Portfolio Standards (see https://www.misoenergy.org/WhatWeDo/StrategicInitiatives/Pages/RenewablePortfolioStandards.aspx).

New information and remaining uncertainties

There are four key uncertainties. The first uncertainty is the net effect of emerging EPA regulations on the future energy mix of the Midwest. Assessments to date suggest a significant number of coal plants will be closed or repowered with lower-carbon natural gas; and even coal plants that are currently thought of as "must run" (to maintain the electric grid's reliability) may be able to be replaced in some circumstances with the right combination of energy efficiency, new transmission lines, demand response, and distributed generation. A second key uncertainty is whether or not natural gas prices will remain at their historically low levels. Given that there are really only five options for meeting electricity demand – energy efficiency, renewables, coal, nuclear, and natural gas – the replacement of coal with natural gas for electricity production would have a significant impact on greenhouse gas emissions in the region. Third is the uncertain future for federal policies that have spurred renewable energy development to date, such as the Production Tax Credit for wind. While prices for both wind and solar continue to fall, the potential loss of tax credits may dampen additional market penetration of these technologies. A fourth uncertainty is the net effect of climate change on energy demand, and the cost of meeting that new demand profile. Research to date suggests the potential for a significant swing from the historically larger demand for heating in the winter to more demand in the summer instead, due to a warmer, more humid climate.[3]

Assessment of confidence based on evidence

There is no dispute about the energy intensity of the midwestern economy, nor its disproportionately large contribution of greenhouse gas emissions. Similarly, there is broad agreement about the Midwest's potential for—and progress toward—lower-carbon electricity production. There is therefore **very high** confidence in this statement.

Key Message #5 Traceable Account

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather and increased precipitation across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Messages 5, 6, and 7) and its Traceable Accounts. Specific details for the Midwest are detailed in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

There is compelling evidence that annual total precipitation has been increasing in the region, with wetter winters and springs, drier summers, an increase in extreme precipitation events, and changes in snowfall patterns. These observations are consistent with climate model projections. Both the observed trends and climate models suggest these trends will increase in the future.

Recent records also indicate evidence of a number of high-impact flood events in the region. Heavy precipitation events cause increased kinetic energy of surface water and thus increase erosion. Heavy precipitation events in the historical records have been shown to be associated with discharge of partially or completely untreated sewage due to the volumes of water overwhelming combined sewer systems that are designed to capture both domestic sewage and stormwater.

Climate downscaling projections tend to indicate an increase in the frequency and duration of extreme events (both heavy precipitation and meteorological drought) in the future.

An extensive literature survey and synthetic analysis is presented in chapters in a recent book[100] for impacts on water quality, transportation, agriculture, health, and infrastructure.

New information and remaining uncertainties

Precipitation is much less readily measured or modeled than air temperature.[3] Thus both historical tendencies and projections for precipitation are inherently less certain than for temperature. Most regional climate models still have a positive bias in precipitation frequency but a negative bias in terms of precipitation amount in extreme events.

Flood records are very heterogeneous and there is some ambiguity about the degree to which flooding is a result of atmospheric conditions.[69] Flooding is not solely the result of incident precipitation but is also a complex function of the preceding conditions such as soil moisture content and extent of landscape infiltration. A key issue (uncertainty) is the future distribution of snowfall. Records indicate that snowfall is decreasing in the southern parts of the region, along with increasing lake effect snow. Climate models predict these trends will increase. There is insufficient knowledge about how this change in snowfall patterns will affect flooding and associated problems, but it is projected to affect the very large spring floods that typically cause the worst flooding in the region. In addition, recent data and climate predictions indicate drier summer conditions, which could tend to offset the effects of higher intensity summer storms by providing increased water storage in the soils. The relative effects of these offsetting trends need to be assessed. To determine future flooding risks, hydrologic modeling is needed that includes the effects of the increase in extreme events, changing snow patterns, and shifts in rainfall patterns. Adaptation measures to reduce soil erosion and combined sewer overflow (CSO) events are available and could be widely adopted.

The impacts of increased magnitude of heavy precipitation events on water quality, agriculture, human health, transportation, and infrastructure will be strongly determined by the degree to which the resilience of such systems is enhanced (for example, some cities are already implementing enhanced water removal systems).

Assessment of confidence based on evidence

There have been improvements in agreement between observed precipitation patterns and model simulations. Also an increase in extreme precipitation events is consistent with first-order reasoning and increased atmospheric water burdens due to increased air temperature. Recent data suggest an increase in flooding in the region but there is uncertainty about how changing snow patterns will affect flood events in the future. Thus there is **high** confidence in increases in high-magnitude rainfall events and extreme precipitation events, and that these trends are expected to continue.

There is **medium** confidence that, in the absence of substantial adaptation actions, the enhancement in extreme precipitation and other tendencies in land use and land cover result in a projected increase in flooding. There is **medium** confidence that, in the absence of major adaptation actions, the enhancement in extreme precipitation will tend to increase the risk of erosion, declines in water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.[3]

Key Message #6 Traceable Account

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for changes in ice cover due to increased temperatures across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 11) and its Traceable Accounts. Specific details for the Midwest are detailed in “Climate Trends and Scenarios for the U.S. National Climate Assessment”[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Altered fish communities: Warmer lakes and streams will certainly provide more habitat for warmwater species as conditions in northern reaches of the basin become more suitable for warmwater fish and as lakes and streams are vacated by cool- and coldwater species.[84] Habitat for coldwater fish, though not expected to disappear, will shrink substantially, though it could also expand in some areas, such as Lake Superior. Whether climate change expands the range of any type of fish is dependent on the availability of forage fish, as higher temperatures also necessitate greater food intake.

Increased abundances of invasive species: As climate change alters water temperatures, habitat, and fish communities, conditions that once were barriers to alien species become conduits for establishment and spread.[84] This migration will alter drastically the fish communities of the Great Lakes basin. Climate change is also projected to heighten the impact of invasive species already present in the Great Lakes basin. Warmer winter conditions, for instance, have the potential to benefit alewife, round gobies, ruffe, sea lamprey, rainbow smelt, and other non-native species. These species have spread rapidly throughout the basin and have already inflicted significant ecological and economic harm.

Declining beach health and harmful algal blooms: Extreme events increase runoff, adding sediments, pollutants, and nutrients to the Great Lakes. The Midwest has experienced rising trends in precipitation and runoff. Agricultural runoff, in combination with increased water temperatures, has caused considerable non-point source pollution problems in recent years, with increased phosphorus and nitrogen loadings from farms contributing to more frequent and prolonged occurrences of anoxic "dead zones" and harmful, dense algae growth for long periods. Stormwater runoff that overloads urban sewer systems during extreme events adds to increased levels of toxic substances, sewage, and bacteria in the Great Lakes, affecting water quality, beach health, and human well-being. Increased storm events caused by climate change will lead to an increase in combined sewer overflows.[84]

Decreased ice cover: Increasingly mild winters have shortened the time between when a lake freezes and when it thaws.[101] Scientists have documented a relatively constant decrease in Great Lakes ice cover since the 1970s, particularly for Lakes Superior, Michigan, Huron, and Ontario. The loss of ice cover on the Great Lakes has both ecological and economic implications. Ice serves to protect shorelines and habitat from storms and wave power. Less ice—coupled with more frequent and intense storms—leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.

Water levels: The 2009 NCA[102] included predictions of a significant drop in Great Lakes levels by the end of the century, based on methods of linking climate models to hydrologic models. These methods have been significantly improved by fully coupling the hydrologic cycle among land, lake, and atmosphere.[97] Without accounting for that cycle of interactions, a study[96] concluded that increases in precipitation would be negated by increases in winter evaporation from less ice cover and by increases in summer evaporation and evapotranspiration from warmer air temperatures, under a scenario of continued increases in global emissions (SRES A2 scenario). Declines of 8 inches to 2 feet have been projected by the end of this century, depending on the specific lake in question.[96] A recent comprehensive assessment,[94] however, has concluded that with a continuation of current rising emissions trends (A2), the lakes will experience a slight decrease or even a rise in water levels; the difference from earlier studies is because earlier studies tended to overstress the amount of evapotranspiration expected to occur. The range of potential future lake levels remains large and includes the earlier projected decline. Overall, however, scientists project an increase in precipitation in the Great Lakes region (with extreme events projected to contribute to this increase), which will contribute to maintenance of or an increase in Great Lakes water levels. However, water level changes are not predicted to be uniform throughout the basin.

Shipping: Ice cover is expected to decrease dramatically by the end of the century, possibly lengthening the shipping season and, thus, facilitating more shipping activity. Current science suggests water levels in the Great Lakes are projected to fall slightly or might even rise over the short run. However, by causing even a small drop in water levels, climate change could make the costs of shipping increase substantially. For instance, for every inch of draft a 1000-foot ship gives up, its capacity is reduced by 270 tons.[93] Lightened loads today already add about $200,000 in costs to each voyage.

New information and remaining uncertainties

Key issues (uncertainties) are: Water levels are influenced by the amount of evaporation from decreased ice cover and warmer air temperatures, by evapotranspiration from warmer air temperatures, and by potential increases in inflow from more precipitation. Uncertainties about Great Lakes water levels are high, though most models suggest that the decrease in ice cover will lead to slightly lower water levels, beyond natural fluctuations.

The spread of invasive species into the system is near-certain (given the rate of introductions over the previous 50 years) without major policy and regulatory changes. However, the changes in Great Lakes fish communities are based on extrapolation from known fishery responses to projected responses to expected changing conditions in the basin. Moreover, many variables beyond water temperature and condition affect fisheries, not the least of which is the availability of forage fish. Higher water temperatures necessitate greater food intake, yet the forage base is changing rapidly in many parts of the Great Lakes basin, thus making the projected impact of climate change on fisheries difficult to discern with very high certainty.

Assessment of confidence based on evidence

Peer-reviewed literature about the effects of climate change are in broad agreement that air and surface water temperatures are rising and will continue to do so, that ice cover is declining steadily, and that precipitation and extreme events are on the rise. For large lake ecosystems, these changes have well-documented effects, such as effects on algal production, stratification (change in water temperature with depth), beach health, and fisheries. Key uncertainties exist about Great Lakes water levels and the impact of climate change on fisheries.

A qualitative summary of climate stressors and coastal margin vulnerabilities for the Great Lakes is given in a technical input report.[84] We have high confidence that the sum of these stressors will exceed the risk posed by any individual stressor. However, quantifying the cumulative impacts of those stressors is very challenging.

Given the evidence and remaining uncertainties, there is **very high** confidence in this key message, except **high** confidence for lake levels changing, and **high** confidence that declines in ice cover will continue to lengthen the commercial navigation season. There is limited information regarding exactly how invasive species may respond to changes in the regional climate, resulting in **medium** confidence for that part of the key message.

Climate Change Impacts in the United States

CHAPTER 19
GREAT PLAINS

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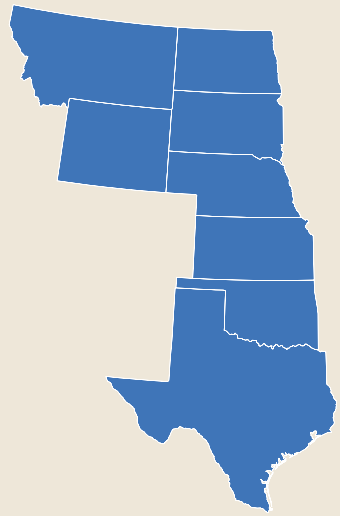

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On the Web: http://nca2014.globalchange.gov/report/regions/great-plains

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

19 GREAT PLAINS

Key Messages

1. **Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.**
2. **Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices.**
3. **Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.**
4. **Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.**
5. **The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.**

The Great Plains is a diverse region where climate and water are woven into the fabric of life. Day-to-day, month-to-month, and year-to-year changes in the weather can be dramatic and challenging for communities and their commerce. The region experiences multiple climate and weather hazards, including floods, droughts, severe storms, tornadoes, hurricanes, and winter storms. In much of the Great Plains, too little precipitation falls to replace that needed by humans, plants, and animals. These variable conditions in the Great Plains already stress communities and cause billions of dollars in damage; climate change will add to both stress and costs.

The people of the Great Plains historically have adapted to this challenging climate. Although projections suggest more frequent and more intense droughts, severe rainfall events, and heat waves, communities and individuals can reduce vulnerabilities through the use of new technologies, community-driven policies, and the judicious use of resources. Adaptation (means of coping with changed conditions) and mitigation (reducing emissions of heat-trapping gases to reduce the speed and amount of climate change) choices can be locally driven, cost effective, and beneficial for local economies and ecosystem services.

USFWS

Temperature and Precipitation Distribution in the Great Plains

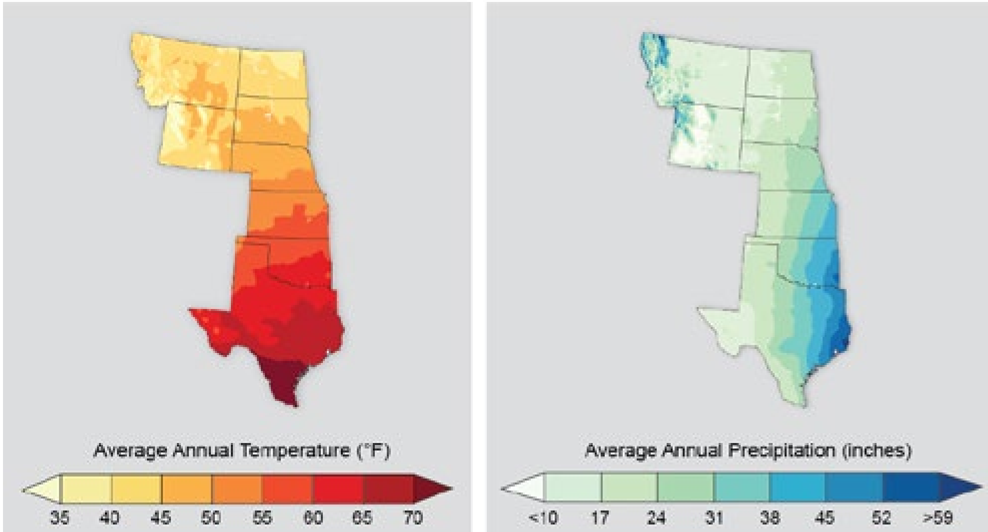


Figure 19.1. The region has a distinct north-south gradient in average temperature patterns (left), with a hotter south and colder north. For precipitation (right), the regional gradient runs west-east, with a wetter east and a much drier west. Averages shown here are for the period 1981-2010. (Figure source: adapted from Kunkel et al. 2013[4]).

Significant climate-related challenges are expected to involve 1) resolving increasing competition among land, water, and energy resources; 2) developing and maintaining sustainable agricultural systems; 3) conserving vibrant and diverse ecological systems; and 4) enhancing the resilience of the region's people to the impacts of climate extremes. These growing challenges will unfold against a changing backdrop that includes a growing urban population and declining rural population, new economic factors that drive incentives for crop and energy production, advances in technology, and shifting policies such as those related to farm and energy subsidies.

The Great Plains region features relatively flat plains that increase in elevation from sea level to more than 5,000 feet at the base of mountain ranges along the Continental Divide. Forested mountains cover western Montana and Wyoming, extensive rangelands spread throughout the Plains, marshes extend along Texas' Gulf Coast, and desert landscapes distinguish far west Texas.[1] A highly diverse climate results from the region's large north-south extent and change of elevation. This regional diversity also means that climate change impacts will vary across the region.

Great Plains residents already must contend with weather challenges from winter storms, extreme heat and cold, severe thunderstorms, drought, and flood-producing rainfall. Texas' Gulf Coast averages about three tropical storms or hurricanes every four years,[2] generating coastal storm surge and sometimes bringing heavy rainfall and damaging winds hundreds of miles inland. The expected rise in sea level will result in the potential for greater damage from storm surge along the Gulf Coast of Texas (see Ch. 25: Coasts).

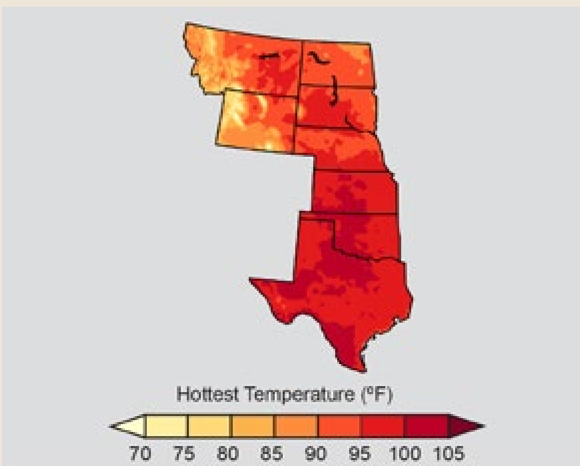
Annual average temperatures range from less than 40°F in the mountains of Wyoming and Montana to more than 70°F in South Texas, with extremes ranging from -70°F in Montana to 121°F in North Dakota and Kansas.[3] Summers are long and hot in the south; winters are long and often severe in the north. North Dakota's increase in annual temperature over the past 130 years is the fastest in the contiguous U.S. and is mainly driven by warming winters.[4]

The region has a distinct north-south gradient in average temperature patterns, with a hotter south and colder north (Figure 19.1). Average annual precipitation greater than 50 inches supports lush vegetation in eastern Texas and Oklahoma. For most places, however, average rainfall is less than 30 inches, with some of Montana, Wyoming, and far west Texas receiving less than 15 inches a year. Across much of the region, annual water loss from transpiration by plants and from evaporation is higher than annual precipitation, making these areas particularly susceptible to droughts.

Projected climate change

For an average of seven days per year, maximum temperatures reach more than 100°F in the Southern Plains and about 95°F in the Northern Plains (Figure 19.2). These high temperatures are projected to occur much more frequently, even under a scenario of substantial reductions in heat-trapping gas (also called greenhouse gas) emissions (B1), with days over 100°F projected to double in number in the north and quadruple in the south by mid-century (Ch. 2: Our Changing Climate, Key Message 7).[4] Similar increases are expected in the number of nights with minimum temperatures higher than 80°F in the south and 60°F in the north (cooler in mountain regions; see Figure 19.3). These increases in extreme heat will have many negative consequences, including increases in surface water losses, heat stress, and demand for air conditioning.[5] These negative consequences will more than offset the benefits of warmer winters, such as lower winter heating demand, less cold stress on humans and animals, and a longer growing season, which will be extended by mid-century an average of 24 days relative to the 1971-2000 average.[4,5] More overwintering insect populations are also expected.[5]

Historical Temperature on the 7 Hottest Days of the Year



The historical (1971-2000) distribution of temperature for the hottest 2% of days (about seven days a year) echoes the distinct north-south gradient in average temperatures.

Projected Change in Number of Hot Days

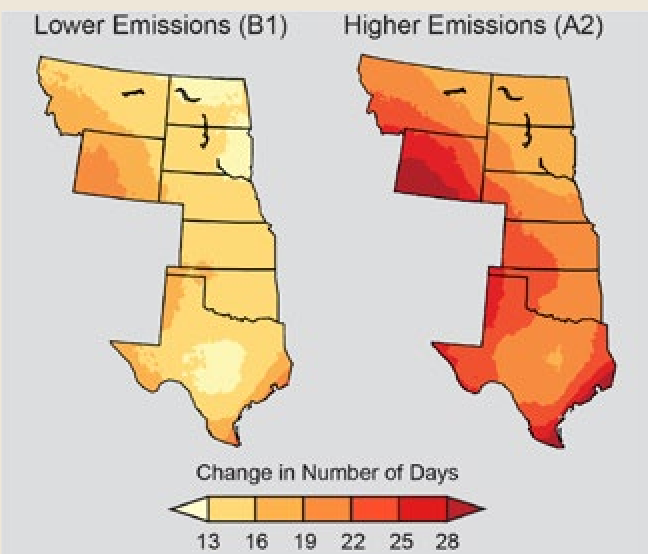
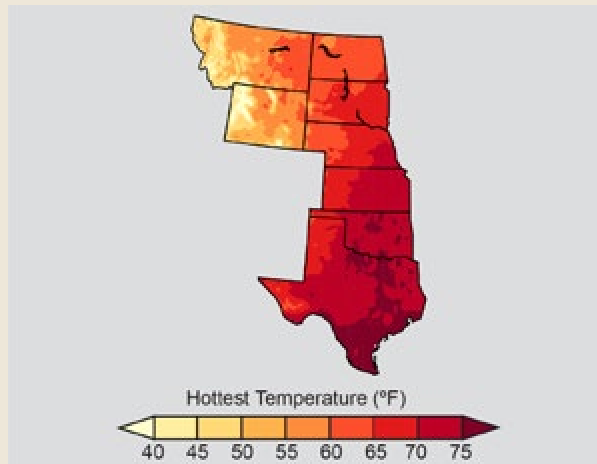


Figure 19.2. The number of days with the hottest temperatures is projected to increase dramatically. By mid-century (2041-2070), the projected change in the number of days exceeding those hottest temperatures is greatest in the western areas and Gulf Coast for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).

Historical Temperature on the 7 Warmest Nights of the Year



The historical (1971-2000) distribution of temperature for the warmest 2% of nights (about seven days a year) echoes the distinct north-south gradient in average temperatures.

Projected Change in Number of Warm Nights

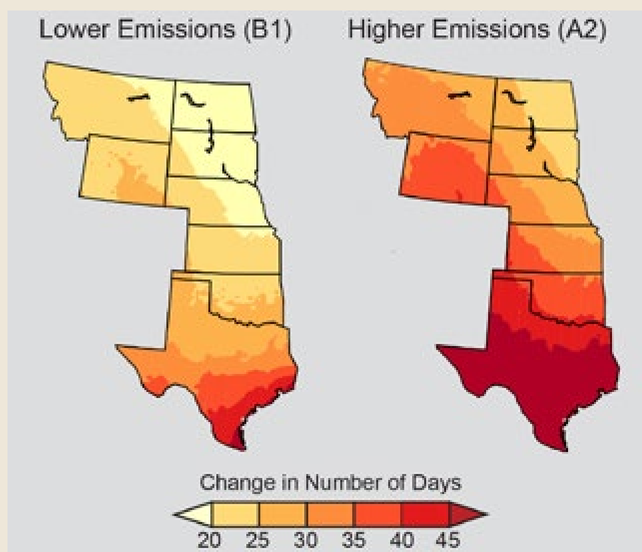
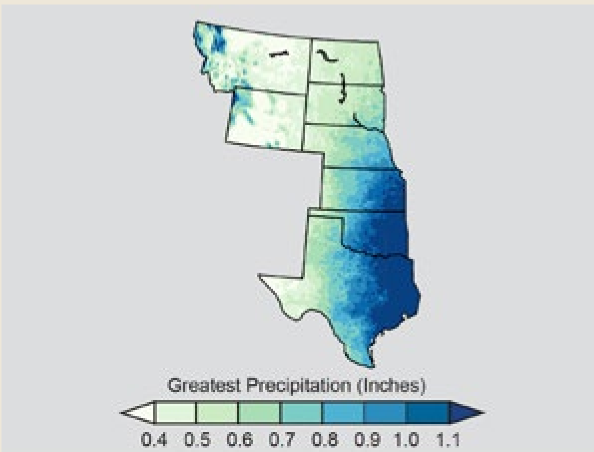


Figure 19.3. The number of nights with the warmest temperatures is projected to increase dramatically. By mid-century (2041-2070), the projected change in number of nights exceeding those warmest temperatures is greatest in the south for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).

Winter and spring precipitation is projected to increase in the northern states of the Great Plains region under the A2 scenario, relative to the 1971-2000 average. In central areas, changes are projected to be small relative to natural variations (Ch. 2: Our Changing Climate, Key Message 5).[4] Projected changes in summer and fall precipitation are small except for summer drying in the central Great Plains, although the exact locations of this drying are uncertain. The number of days with heavy precipitation is expected to increase by mid-century, especially in the north (Ch. 2: Our Changing Climate, Key Message 6). Large parts of Texas and Oklahoma are projected to see longer dry spells (up to 5 more days on average by mid-century). By contrast, changes are projected to be minimal in the north (Ch. 2: Our Changing Climate, Key Message 7).[4]

Historical Amount of Precipitation on the 7 Wettest Days of the Year



The historical (1971-2000) distribution of the greatest 2% of daily precipitation (about seven days a year) echoes the regional west-east gradient in average precipitation.

Projected Change in Number of Heavy Precipitation Days

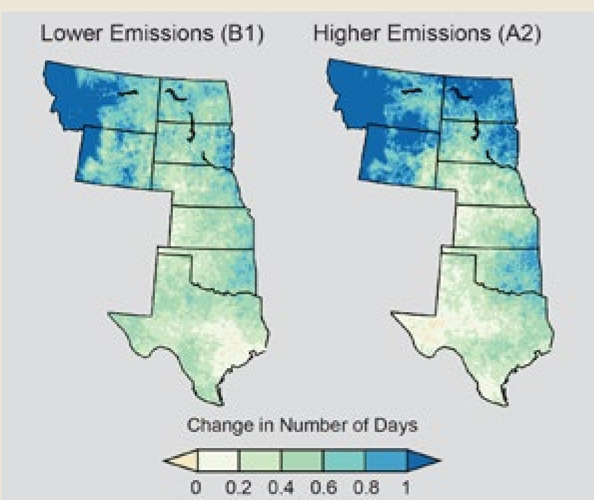


Figure 19.4. The number of days with the heaviest precipitation is not projected to change dramatically. By mid-century (2041-2070), the projected change in days exceeding those precipitation amounts remains greatest in the northern area for both the lower emissions scenario (B1) and for the higher emissions scenario (A2). (Figure source: NOAA NCDC / CICS-NC).

Projected Change in Number of Consecutive Dry Days

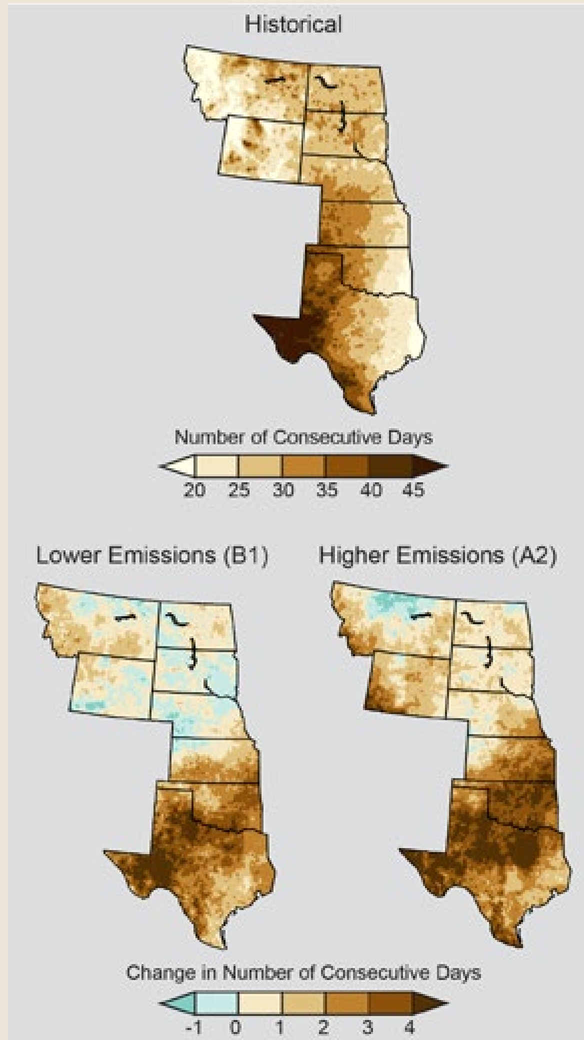


Figure 19.5. Current regional trends of a drier south and a wetter north are projected to become more pronounced by mid-century (2041-2070 as compared to 1971-2000 averages). Maps show the maximum annual number of consecutive days in which limited (less than 0.01 inches) precipitation was recorded on average from 1971 to 2000 (top), projected changes in the number of consecutive dry days assuming substantial reductions in emissions (B1), and projected changes if emissions continue to rise (A2). The southeastern Great Plains, which is the wettest portion of the region, is projected to experience large increases in the number of consecutive dry days. (Figure source: NOAA NCDC / CICS-NC).

Key Message 1: Energy, Water and Land Use

Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.

Energy, water, and land use are inherently interconnected,[6] and climate change is creating a new set of challenges for these critical sectors (Ch. 2: Our Changing Climate; Ch. 10: Energy, Water, and Land).[7,8,9] The Great Plains is rich with energy resources, primarily from coal, oil, and natural gas, with growing wind and biofuel industries.[10] Texas produces 16% of U.S. energy (mostly from crude oil and natural gas), and Wyoming provides an additional 14% (mostly from coal). North Dakota is the second largest producer of oil in the Great Plains, behind Texas. Nebraska and South Dakota rank third and fifth in biofuel production, and five of the eight Great Plains states have more than 1,000 megawatts of installed wind generation capacity, with Texas topping the list.[11] More than 80% of the region's land area is used for agriculture, primarily cropland, pastures, and rangeland. Other land uses include forests, urban and rural development, transportation, conservation, and industry.

Significant amounts of water are used to produce energy[7,12] and to cool power plants.[13] Electricity is consumed to collect, purify, and pump water. Although hydraulic fracturing to release oil and natural gas is a small component of total water use,[14] it can be a significant proportion of water use in local and rural groundwater systems. Energy facilities, transmission lines, and wind turbines can fragment both natural habitats and agriculture lands (Ch. 10: Energy, Water, and Land).[5]

The trend toward more dry days and higher temperatures across the south will increase evaporation, decrease water supplies, reduce electricity transmission capacity, and increase cooling demands. These changes will add stress to limited water resources and affect management choices related to irrigation, municipal use, and energy generation.[15] In the Northern Plains, warmer winters may lead to reduced heating demand while hotter summers will increase demand for air conditioning, with the summer increase in demand outweighing the winter decrease (Ch. 4: Energy, Key Message 2).[15]

Changing extremes in precipitation are projected across all seasons, including higher likelihoods of both increasing heavy rain and snow events[4] and more intense droughts (Ch. 2: Our Changing Climate, Key Messages 5 and 6).[16] Winter and spring precipitation and very heavy precipitation events are both projected to increase in the northern portions of the area, leading to increased runoff and flooding that will reduce water quality and erode soils. Increased snowfall, rapid spring warming, and intense rainfall can combine to produce devastating floods, as is already common along the Red River of the North. More intense rains will also contribute to urban flooding.

Increased drought frequency and intensity can turn marginal lands into deserts. Reduced per capita water storage will continue to increase vulnerability to water shortages.[17] Federal and state legal requirements mandating water allocations for ecosystems and endangered species add further competition for water resources.

Diminishing water supplies and rapid population growth are critical issues in Texas. Because reservoirs are limited and have high evaporation rates, San Antonio has turned to the Edwards Aquifer as a major source of groundwater storage. Nineteen water districts joined to form a Regional Water Alliance for sustainable water development through 2060. The alliance creates a competitive market for buying and selling water rights and simplifies transfer of water rights.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Key Message 2: Sustaining Agriculture

Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices

The important agricultural sector in the Great Plains, with a total market value of about $92 billion (the most important being crops at 43% and livestock at 46%),[18] already contends with significant climate variability (Ch. 6: Agriculture). Projected changes in climate, and human responses to it, will affect aspects of the region's agriculture, from the many crops that rely solely on rainfall, to the water and land required for increased energy production from plants, such as fuels made from corn or switchgrass (see Ch. 10: Energy, Water, and Land).

Water is central to the region's productivity. The High Plains Aquifer, including the Ogallala, is a primary source for irrigation.[19] In the Northern Plains, rain recharges this aquifer quickly, but little recharge occurs in the Southern Plains.[20,21]

Projected changes in precipitation and temperature have both positive and negative consequences to agricultural productivity in the Northern Plains. Projected increases in winter and spring precipitation in the Northern Plains will benefit agricultural productivity by increasing water availability through soil moisture reserves during the early growing season, but this can be offset by fields too wet to plant. Rising temperatures will lengthen the growing season, possibly allowing a second annual crop in some places and some years. Warmer winters pose challenges.[22,23,24] For example, some pests and invasive weeds will be able to survive the warmer winters.[25] Winter crops that leave dormancy earlier are susceptible to spring freezes.[26] Rainfall events already have become more intense,[27] increasing erosion and nutrient runoff, and projections are that the frequency and severity of these heavy rainfall events will increase.[4,28] The Northern Plains will remain vulnerable to periodic drought because much of the projected increase in precipitation is expected to occur in the cooler months while increasing temperatures will result in additional evapotranspiration.

In the Central and Southern Plains, projected declines in precipitation in the south and greater evaporation everywhere due to higher temperatures will increase irrigation demand and exacerbate current stresses on agricultural productivity. Increased water withdrawals from the Ogallala Aquifer and High Plains Aquifer would accelerate ongoing depletion in the southern parts of the aquifers and limit the ability to irrigate.[21,29] Holding other aspects of production constant, the climate impacts of shifting from irrigated to dryland agriculture would reduce crop yields by about a factor of two.[30] Under these climate-induced changes, adaptation of agricultural practices will be needed, however, there may be constraints on social-ecological adaptive capacity to make these adjustments (see also Ch. 28: Adaptation).

Increases in Irrigated Farmland in the Great Plains

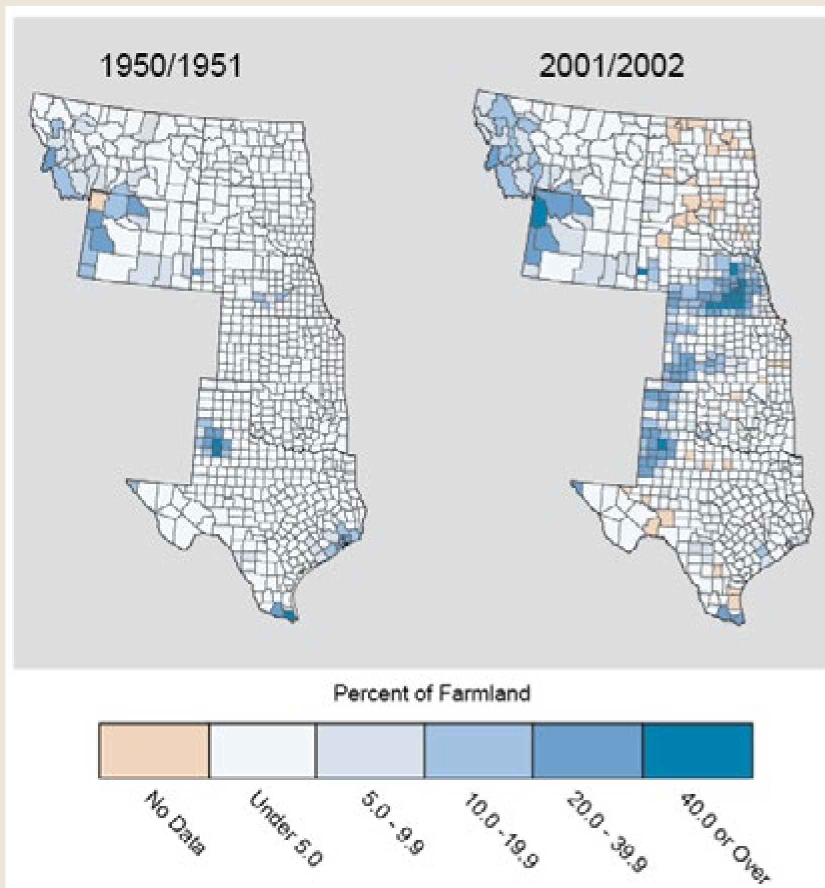

Figure 19.6. Irrigation in western Kansas, Oklahoma, and Texas supports crop development in semiarid areas. Declining aquifer levels threaten the ability to maintain production. Some aquifer-dependent regions, like southeastern Nebraska, have seen steep rises in irrigated farmland, from around 5% to more than 40%, during the period shown. (Figure source: reproduced from Atlas of the Great Plains by Stephen J. Lavin, Clark J. Archer, and Fred M. Shelley by permission of the University of Nebraska. Copyright 2011 by the Board of Regents of the University of Nebraska[33]).

The projected increase in high temperature extremes and heat waves will negatively affect livestock and concentrated animal feeding operations.[31] Shortened dormancy periods for winter wheat will lessen an important source of feed for the livestock industry. Climate change may thus result in a northward shift of crop and livestock production in the region. In areas projected to be hotter and drier in the future, maintaining agriculture on marginal lands may become too costly.

Adding to climate change related stresses, growing water demands from large urban areas are also placing stresses on limited water supplies. Options considered in some areas include groundwater development and purchasing water rights from agricultural areas for transfer to cities.[32]

During the droughts of 2011 and 2012, ranchers liquidated large herds due to lack of food and water. Many cattle were sold to slaughterhouses; others were relocated to other pastures through sale or lease. As herds are being rebuilt, there is an opportunity to improve genetic stock, as those least adapted to the drought conditions were the first to be sold or relocated. Some ranchers also used the drought as an opportunity to diversify their portfolio, managing herds in both Texas and Montana.

Key Message 3: Conservation and Adaptation

Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.

Land development for energy production, land transformations on the fringes of urban areas, and economic pressures to remove lands from conservation easements pose threats to natural systems in the Great Plains.[34] Habitat fragmentation is already a serious issue that inhibits the ability of species to migrate as climate variability and change alter local habitats.[35] Lands that remain out of production are susceptible to invasion from non-native plant species.

Many plant and animal species are responding to rising temperatures by adjusting their ranges at increasingly greater rates.[36] These adjustments may also require movement of species that have evolved to live in very specific habitats, which may prove increasingly difficult for these species. The historic bison herds migrated to adapt to climate, disturbance, and associated habitat variability,[37] but modern land-use patterns, roads, agriculture, and structures inhibit similar large-scale migration.[38] In the playa regions of the southern Great Plains, agricultural practices have modified more than 70% of seasonal lakes larger than 10 acres, and these lakes will be further altered under warming conditions.[39,40] These changes in seasonal lakes will further affect bird populations[41] and fish populations[42] in the region.

Observed climate-induced changes have been linked to changing timing of flowering, increases in wildfire activity and pest outbreaks, shifts in species distributions, declines in the abundance of native species, and the spread of invasive species (Ch. 8: Ecosystems). From Texas to Montana, altered flowering patterns due to more frost-free days have increased the length of pollen season for ragweed by as many as 16 days over the period from 1995 to 2009.[43] Earlier snowmelt in Wyoming from 1961 to 2002 has been related to the American pipit songbird laying eggs about 5 days earlier.[44] During the past 70 years, observations indicate that winter wheat is flowering 6 to 10 days earlier as spring temperatures have risen.[23] Some species may be less sensitive to changes in temperature and precipitation, causing first flowering dates to change for some species but not for others.[22] Even small shifts in timing, however, can disrupt the integrated balance of ecosystem functions like predator-prey relationships, mating behavior, or food availability for migrating birds.

In addition to climate changes, the increase in atmospheric CO_2 concentrations may offset the drying effects from warming by considerable improvements in plant water-use efficiency, which occur as CO_2 concentrations increase.[45] However, nutrient content of the grassland communities may be decreased under enriched CO_2 environments, affecting nutritional quality of the grasses and leaves eaten by animals.

The interaction of climate and land-use changes across the Great Plains promises to be challenging and contentious. Opportunities for conservation of native grasslands, including species and processes, depend primarily and most immediately on managing a fragmented network of untilled prairie. Restoration of natural processes, conservation of remnant species and habitats, and consolidation/connection of fragmented areas will facilitate conservation of species and ecosystem services across the Great Plains. However, climate change will complicate current conservation efforts as land fragmentation continues to reduce habitat connectivity. The implementation of adaptive management approaches provides robust options for multiple solutions.

Sage grouse and climate change

Habitat fragmentation inhibits the ability of species such as the Greater Sage Grouse, a candidate for Endangered Species Act protections, to migrate in response to climate change. Its current habitat is threatened by energy development, agricultural practices, and urban development. Rapid expansion of oil and gas fields in North Dakota, Wyoming, and Montana and development of wind farms from North Dakota through Texas are opening new lands to development and contributing to habitat fragmentation of important core Sage Grouse habitat.[46] The health of Sage Grouse habitat is associated with other species' health as well.[47] Climate change projections also suggest a shift in preferred habitat locations and increased susceptibility to West Nile Virus.[48]

Historical and Current Range of Sage Grouse Habitat

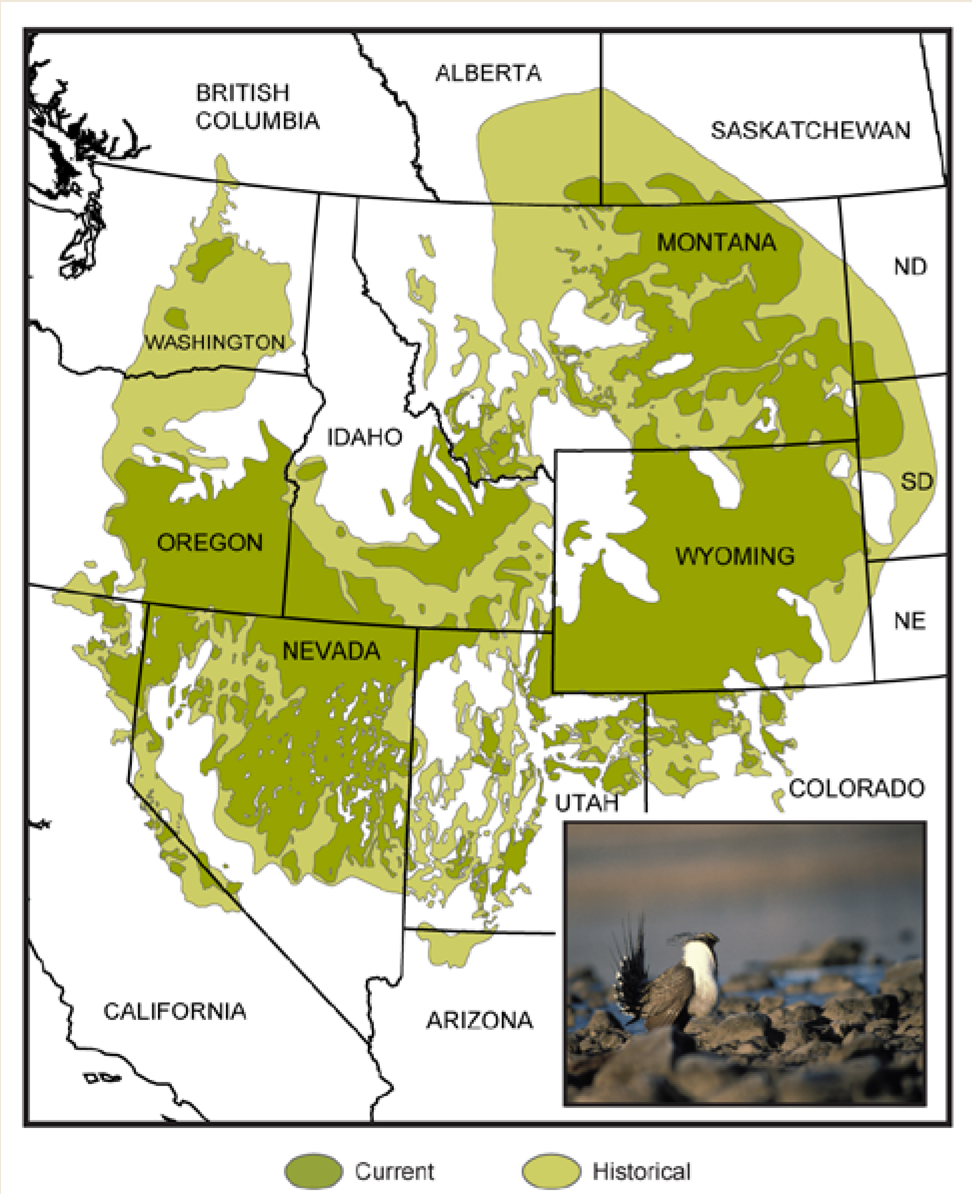

Figure 19.7. Comparing estimates of Greater Sage Grouse distribution from before settlement of the area (light green: prior to about 1800) with the current range (dark green: 2000) shows fragmentation of the sagebrush habitat required by this species. Over the last century, the sagebrush ecosystem has been altered by fire, invasion by new plant species, and conversion of land to agriculture, causing a decline in Sage Grouse populations. (Figure source: adapted from Aldridge et al. 2008.[49] Photo credit: U.S. Fish and Wildlife Service, Wyoming Ecological Services).

Key Message 4: Vulnerable Communities

Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.

The Great Plains is home to a geographically, economically, and culturally diverse population. For rural and tribal communities, their remote locations, sparse development, limited local services, and language barriers present greater challenges in responding to climate extremes. Working-age people are moving to urban areas, leaving a growing percentage of elderly people in rural communities (see also Ch. 14: Rural Communities).

Overall population throughout the region is stable or declining, with the exception of substantial increases in urban Texas, tribal communities, and western North Dakota, related in large part to rapid expansion of energy development.[50] Growing urban areas require more water, expand into forests and cropland, fragment habitat, and are at a greater risk of wildfire – all factors that interplay with climate.

Populations such as the elderly, low-income, and non-native English speakers face heightened climate vulnerability. Public health resources, basic infrastructure, adequate housing, and effective communication systems are often lacking in com-

Population Change in the Great Plains

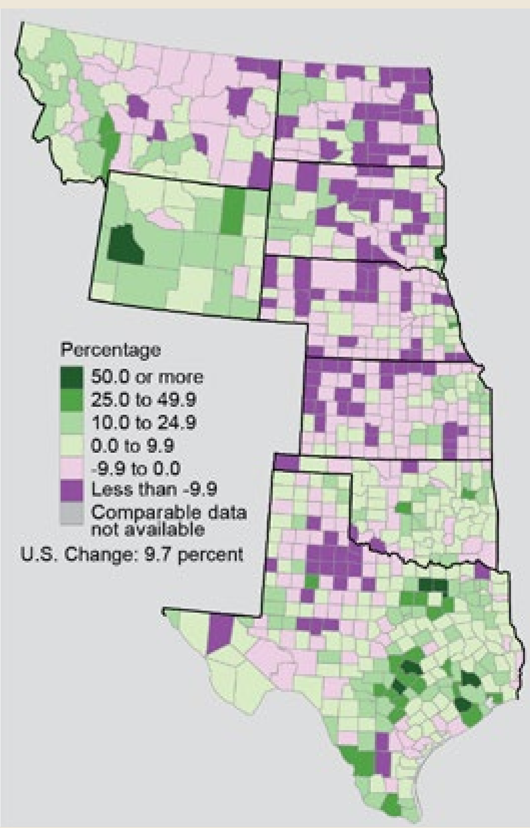

Figure 19.8. Demographic shifts continue to reshape communities in the Great Plains, with many central Great Plains communities losing residents. Rural and tribal communities will face additional challenges in dealing with climate change impacts due to demographic changes in the region (Ch. 14: Rural Communities; Ch. 12: Indigenous Peoples). Figure shows population change from 2000 to 2010. (Figure source: U.S. Census Bureau 2010[57]).

Tribal Populations in the Great Plains

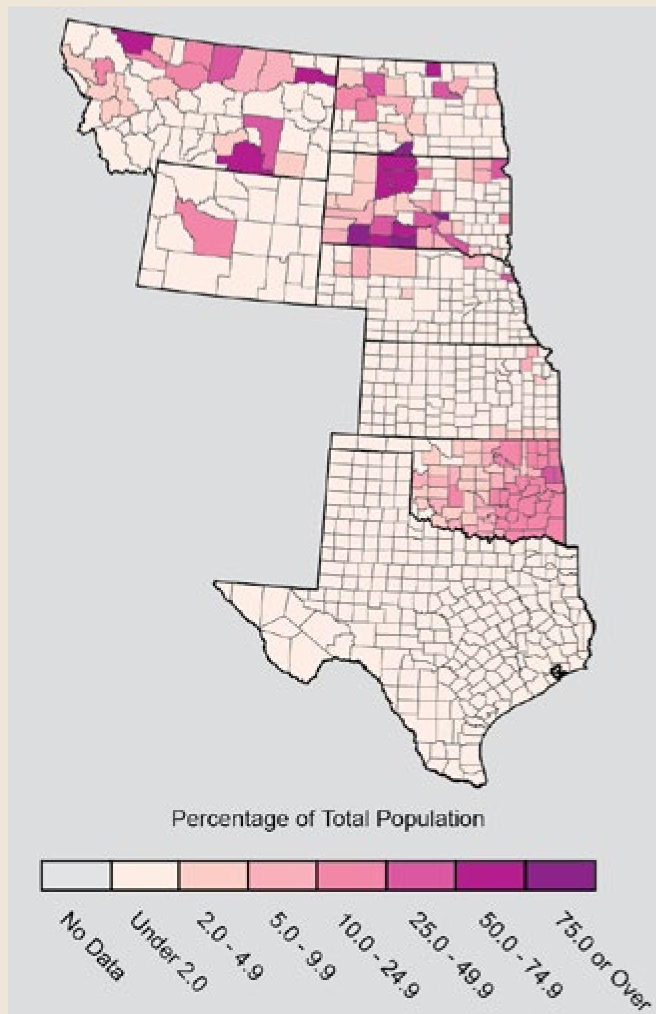

Figure 19.9. Tribal populations in the Great Plains are concentrated near large reservations, like various Sioux tribes in South Dakota and Blackfeet and Crow reservations in Montana; and in Cherokee, Chickasaw, Choctaw, and other tribal lands in Oklahoma (Figure source: reproduced from Atlas of the Great Plains by Stephen J. Lavin, Clark J. Archer, and Fred M. Shelley by permission of the University of Nebraska. Copyright 2011 by the Board of Regents of the University of Nebraska[33]).

munities that are geographically, politically, and economically isolated.[51] Elderly people are more vulnerable to extreme heat, especially in warmer cities and communities with minimal air conditioning or sub-standard housing.[52] Language barriers for Hispanics may impede their ability to plan for, adapt to, and respond to climate-related risks.[53]

The 70 federally recognized tribes in the Great Plains are diverse in their land use, with some located on lands reserved from their traditional homelands, and others residing within territories designated for their relocation, as in Oklahoma (see also Ch. 12: Indigenous Peoples). While tribal communities have adapted to climate change for centuries, they are now constrained by physical and political boundaries.[54] Traditional ecosystems and native resources no longer provide the support they used to.[55] Tribal members have reported the decline or disappearance of culturally important animal species, changes in the timing of cultural ceremonies due to earlier onset of spring, and the inability to locate certain types of ceremonial wild plants.[56]

Key Message 5: Opportunities to Build Resilience

The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.

The Great Plains is an integrated system. Changes in one part, whether driven by climate or by human decisions, affect other parts. Some of these changes are already underway, and many pieces of independent evidence project that ongoing climate-related changes will ripple throughout the region.

Many of these challenges will cut across sectors: water, land use, agriculture, energy, conservation, and livelihoods. Competition for water resources will increase within already-stressed human and ecological systems, particularly in the Southern Plains, affecting crops, energy production, and how well people, animals, and plants can thrive. The region's ecosystems, economies, and communities will be further strained by increasing intensity and frequency of floods, droughts, and heat waves that will penetrate into the lives and livelihoods of Great Plains residents. Although some communities and

Oglala Lakota Respond to Climate Change

The Oglala Lakota tribe in South Dakota is incorporating climate change adaptation and mitigation planning as they consider long-term sustainable development planning. Their *Oyate Omniciye* plan is a partnership built around six livability principles related to transportation, housing, economic competitiveness, existing communities, federal investments, and local values. Interwoven with this is a vision that incorporates plans to reduce future climate change and adapt to future climate change, while protecting cultural resources.[58]


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states have made efforts to plan for these projected changes, the magnitude of the adaptation and planning efforts do not match the magnitude of the expected changes.

Successful adaptation of human and natural systems to climate change would benefit from:

- recognition of and commitment to addressing these challenges;
- regional-scale planning and local-to-regional implementation;[8,59]
- mainstreaming climate planning into existing natural resource, public health, and emergency management processes;[60]
- renewed emphasis on restoration of ecological systems and processes;[61]
- recognition of the value of natural systems to sustaining life;[62,63]
- sharing information among decision-makers; and
- enhanced alignment of social and ecological goals.[64]

Communities already face tradeoffs in efforts to make efficient and sustainable use of their resources. Jobs, infrastructure, and tax dollars that come with fossil fuel extraction or renewable energy production are important, especially for rural communities. There is also economic value in the conversion of native grasslands to agriculture. Yet the tradeoffs among this development, the increased pressure on water resources, and the effects on conservation need to be considered if the region is to develop climate-resilient communities.

Untilled prairies used for livestock grazing provide excellent targets for native grassland conservation. Partnerships among many different tribal, federal, state, local, and private landowners can decrease landscape fragmentation and help manage the connection between agriculture and native habitats. Soil and wetland restoration enhances soil stability and health, water conservation, aquifer recharge, and food sources for wildlife and cattle. Healthy species and ecosystem services support social and economic systems where local products, tourism, and culturally significant species accompany large-scale agriculture, industry, and international trade as fundamental components of society.

Although there is tremendous adaptive potential among the diverse communities of the Great Plains, many local government officials do not yet recognize climate change as a problem that requires proactive planning.[60,65] Positive steps toward greater community resilience have been achieved through local and regional collaboration and increased two-way communication between scientists and local decision-makers (see Ch. 28: Adaptation). For example, the Institute for Sustainable Communities conducts Climate Leadership Academies that promote peer learning and provides direct technical assistance to communities in a five-state region in the Southwest as part of their support of the Western Adaptation Alliance.[66] Other regions have collaborated to share information, like the Southeast Florida Regional Compact 2012. Programs such as NOAA's Regional Integrated Sciences and Assessments (RISA) support scientists working directly with communities to help build capacity to prepare for and adapt to both climate variability and climate change.[67] Climate-related challenges can be addressed with creative local engagement and prudent use of community assets.[68] These assets include social networks, social capital, indigenous and local knowledge, and informal institutions.

The summer of 2011

Future climate change projections include more precipitation in the Northern Great Plains and less in the Southern Great Plains. In 2011, such a pattern was strongly manifest, with exceptional drought and recording-setting temperatures in Texas and Oklahoma and flooding in the Northern Great Plains.

Many locations in Texas and Oklahoma experienced more than 100 days over 100ºF. Both states set new records for the hottest summer since record keeping began in 1895. Rates of water loss due in part to evaporation were double the long-term average. The heat and drought depleted water resources and contributed to more than $10 billion in direct losses to agriculture alone. These severe water constraints strained the ability to meet electricity demands in Texas during 2011 and into 2012, a problem exacerbated by the fact that Texas is nearly isolated from the national electricity grid.

These recent temperature extremes were attributable in part to human-induced climate change (approximately 20% of the heat wave magnitude and a doubling of the chance that it would occur).[69] In the future, average temperatures in this region are expected to increase and will continue to contribute to the intensity of heat waves (Ch. 2: Our Changing Climate, Key Messages 3 and 7).

Days Above 100ºF in Summer 2011

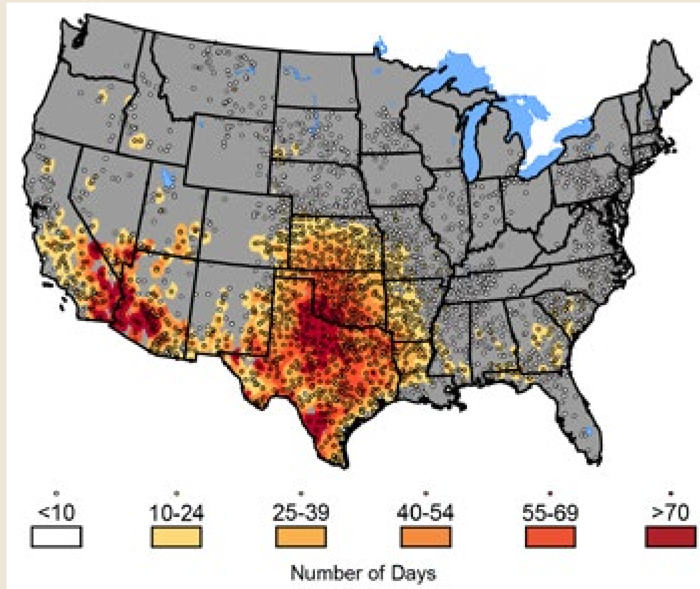

Figure 19.10. In 2011, cities including Houston, Dallas, Austin, Oklahoma City, and Wichita, among others, all set records for the highest number of days recording temperatures of 100°F or higher in those cities' recorded history. The black circles denote the location of observing stations recording 100°F days. (Figure source: NOAA NCDC 2012[3]).

By contrast to the drought in the Southern Plains, the Northern Plains were exceptionally wet in 2011, with Montana and Wyoming recording all-time wettest springs and the Dakotas and Nebraska not far behind. Record rainfall and snowmelt combined to push the Missouri River and its tributaries beyond their banks and leave much of the Crow Reservation in Montana underwater. The Souris River near Minot, North Dakota, crested at four feet above its previous record, with a flow five times greater than any in the past 30 years. Losses from the flooding were estimated at $2 billion.

A Texas State Park police officer walks across a cracked lakebed in August 2011. This lake once spanned more than 5,400 acres.

Increases in heavy downpours contribute to flooding.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Traceable Accounts

Process for Developing Key Messages:
A central component of the assessment process was the Great Plains Regional Climate assessment workshop that was held in August 2011 in Denver, CO, with approximately 40 attendees. The workshop began the process leading to a foundational Technical Input Report (TIR), the Great Plains Regional Climate Assessment Technical Report.[5] The TIR consists of 18 chapters assembled by 37 authors representing a wide range of inputs including governmental agencies, non-governmental organizations, tribes, and other entities.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful review of the foundational TIR[8] and of approximately 50 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions were followed by expert deliberation of draft key messages by the authors during an in-person meeting in Kansas City in April 2012, wherein each message was defended before the entire author team prior to the key message being selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities".

Key message #1 Traceable Account

Rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Temperatures are rising across the United States (Ch. 2: Our Changing Climate, Key Message 3 and its Traceable Account). Specific details for the Great Plains are provided in the Regional Climate Trends and Scenarios for the U.S. National Climate Assessment[4] with its references.

Rising temperatures impact energy and water (Ch.10: Energy, Water, and Land; Ch. 4: Energy). Publications have explored the projected increase in water competition and stress for natural resources[7,13,14,17] and the fragmentation of natural habitats and agricultural lands.[8] These sources provided numerous references that were drawn from to lead to this key message.

New information and remaining uncertainties
A key uncertainty is the exact rate and magnitude of the projected changes in precipitation, because high inter-annual variability may either obscure or highlight the long-term trends over the next few years.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Also unknown is ecological demand for water. Water use by native and invasive species under current climate needs to be quantified so that it can be modeled under future scenarios to map out potential impact envelopes. There is also uncertainty over the projections of changes in precipitation due to difficulty of modeling projections of convective precipitation, which is the primary source of water for most of the Great Plains.

Assessment of confidence based on evidence

Very High for all aspects of the key message. The relationship between increased temperatures and higher evapotranspiration is well established. Model projections of higher temperatures are robust. Confidence is highest for the southern Great Plains, where competition among sectors, cities, and states for future supply is already readily apparent, and where population growth (demand-side) and projected increases in precipitation deficits are greatest.

Key message #2 Traceable Account

Changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Great Plains Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for altered precipitation across the U.S. is discussed in Ch. 2: Our Changing Climate, Key Message 5 and 6 and their Traceable Accounts. Specific details for the Great Plains, such as warming winters and altered rainfall events are in the Climate Trends and Scenarios for the U.S. National Climate Assessment[4] with its references.

Limitations of irrigation options in the High Plains aquifer have been detailed.[21] The impacts of shifting from irrigated to rain-fed agriculture have also been detailed.[30] Studies document negative impacts on livestock production through the Great Plains.[31]

New information and remaining uncertainties

A key issue (uncertainty) is rainfall patterns. Although models show a general increase in the northern Great Plains and a decrease in the southern Great Plains, the diffuse gradient between the two leaves uncertain the location of greatest impacts on the hydrologic cycle. Timing of precipitation is critical to crop planting, development and harvesting; shifts in seasonality of precipitation therefore need to be quantified. Rainfall patterns will similarly affect forage production, particularly winter wheat that is essential to cattle production in the southern Great Plains.

Assessment of confidence based on evidence

The general pattern of precipitation changes and overall increases in temperature are robust. The implications of these changes are enormous, although assessing changes in more specific locations is more uncertain. Our assessment is based on the climate projections and known relationships to crops (for example, corn not being able to "rest" at night due to high minimum temperatures), but pinpointing where these impacts will occur is difficult. Additionally, other factors that influence productivity, such as genetics, technological change, economic incentives, and federal and state policies, can alter or accelerate the impacts. Given the evidence and remaining uncertainties, agriculture and livestock management practices will need to adjust to these changes in climate and derived aspects although specific changes are yet to be determined. Overall, confidence is **high**.

Key message #3 Traceable Account

Landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Great Plains Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of publications have explored the changes in habitat composition,[39] plant distribution and development cycles [22,23,43] and animal distributions.[36,38,44]

New information and remaining uncertainties

In general, the anticipated carbon dioxide enrichment, warming, and increase in precipitation variability influence vegetation primarily by affecting soil-water availability to plants. This is especially important as the transition between water surplus and water deficit (based on precipitation minus evapotranspiration) occurs across the Great Plains, with eastern areas supporting more biomass than western areas, especially given the current east-to-west difference in precipitation and the vegetation it supports.[1] These effects are evident in experiments with each of the individual aspects of climate change.[45] It is difficult to project, however, all of the interactions with all of the vegetative species of the Great Plains, so as to better manage ecosystems.

Several native species have been in decline due to habitat fragmentation, including quail, ocelots, and lesser prairie chickens.[46] Traditional adaptation methods of migration common to the Great Plains, such as bison herds had historically done, are less of an option as animals are confined to particular locations due to habitat fragmentation. As habitats change due to invasive species of plant and animals and as climate change reduces viability of native vegetation, the current landscapes may be incapable of supporting these wildlife populations.[38]

Assessment of confidence based on evidence

Confidence is **very high** that landscape is already fragmented and will continue to become more fragmented as energy exploration expands into less suitable agriculture lands that have not been developed as extensively. The effects of carbon dioxide and water availability on individual species are well known, but there is less published research on the interaction among different species. Evidence for the impact of climate change on species is **very high**, but specific adaptation strategies used by these species are less certain. Because of the more limited knowledge on adaptation strategies, we rate this key message overall has having **high** confidence. Our assessment is based upon historical methods, such as migration, used by species across the Great Plains to adapt to previous changes in climate and habitats and the incompatibility of those methods with current land-use practices.

Key message #4 Traceable Account

Communities that are already the most vulnerable to weather and climate extremes will be stressed even further by more frequent extreme events occurring within an already highly variable climate system.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Extreme events are documented for the nation (Ch. 2: Our Changing Climate, Key Message 7), and for the region in the Climate Trends and Scenarios for the U.S. National Climate Assessment.[4]

There are a few studies documenting the vulnerability of communities in remote locations with sparse infrastructure, limited local services, and aging populations (Ch. 14: Rural Communities),[51] with some areas inhibited by language barriers.[53] Changes in the tribal communities have been documented on a number of issues.[54,55,56,58]

New information and remaining uncertainties

A key issue (uncertainty) is how limited financial resources will be dedicated to adaptation actions and the amount of will and attention that will be paid to decreasing vulnerability and increasing resilience throughout the region. Should the awareness of damage grow great enough, it may overcome the economic incentives for development and change perspectives, allowing for increased adaptive response. But if current trends continue, more vulnerable lands may be lost. Thus the outcome on rural and vulnerable populations is largely unknown.

Assessment of confidence based on evidence

Extensive literature exists on vulnerable populations, limited resources and ability to respond to change. However, because the expected magnitude of changes is beyond previous experience and societal response is unknown, so the overall confidence is **high**.

Key message #5 Traceable Account

The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Great Plains Technical Input Report.[5] Technical inputs (47) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

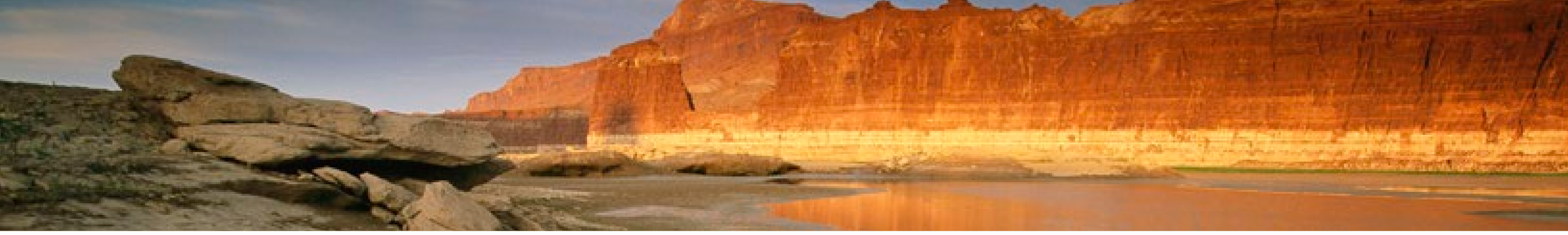
A number of publications have looked at the requirements for adaptation of human and natural systems to climate change. These requirements include large- and small-scale planning,[8,59,62] emphasis on restoring ecological systems and processes,[61] realizing the importance of natural systems,[62,63] and aligning the social and ecological goals.[64]

New information and remaining uncertainties

No clear catalog of ongoing adaptation activities exists for the Great Plains region. Initial steps towards such a catalog have been supported by the National Climate Assessment in association with NOAA's Regional Integrated Sciences and Assessments teams. The short-term nature of many planning activities has been described.[65] Until a systematic assessment is conducted, most examples of adaptation are anecdotal. However, stresses in physical and social systems are readily apparent, as described in the other key messages. How communities, economic sectors, and social groups will respond to these stresses needs further study.

Assessment of confidence based on evidence

Climate trends over the past century, such as North Dakota warming more than any other state in the contiguous U.S., coupled with evidence of ecological changes and projections for further warming indicates **very high** confidence that climate patterns will be substantially different than those of the preceding century. While systematic evidence is currently lacking, emerging studies point toward a proclivity toward short-term planning and incremental adjustment rather than long-term strategies for evolving agricultural production systems, habitat management, water resources and societal changes. Evidence suggests that adaptation is *ad hoc* and isolated and will likely be inadequate to address the magnitude of social, economic, and environmental challenges that face the region. Overall confidence is **medium**.



Climate Change Impacts in the United States

CHAPTER 20
SOUTHWEST

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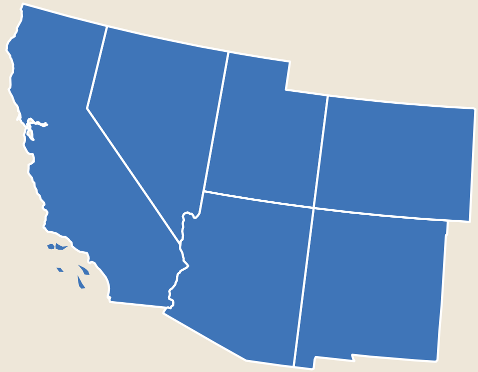

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On the Web: http://nca2014.globalchange.gov/report/regions/southwest

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

20 SOUTHWEST

Key Messages

1. **Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems.**
2. **The Southwest produces more than half of the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increasing temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.**
3. **Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.**
4. **Flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some California coastal areas during storms and extreme high tides. Sea level rise is projected to increase as Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher seas and reach farther inland.**
5. **Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.**

The Southwest is the hottest and driest region in the United States, where the availability of water has defined its landscapes, history of human settlement, and modern economy. Climate changes pose challenges for an already parched region that is expected to get hotter and, in its southern half, significantly drier. Increased heat and changes to rain and snowpack will send ripple effects throughout the region's critical agriculture sector, affecting the lives and economies of 56 million people – a population that is expected to increase 68% by 2050, to 94 million.[1] Severe and sustained drought will stress water sources, already over-utilized in many areas, forcing increasing competition among farmers, energy producers, urban dwellers, and plant and animal life for the region's most precious resource.

The region's populous coastal cities face rising sea levels, extreme high tides, and storm surges, which pose particular risks to highways, bridges, power plants, and sewage treatment plants. Climate-related challenges also increase risks to critical port cities, which handle half of the nation's incoming shipping containers.

Agriculture, a mainstay of the regional and national economies, faces uncertainty and change. The Southwest produces more than half of the nation's high-value specialty crops, including certain vegetables, fruits, and nuts. The severity of future impacts will depend upon the complex interaction of pests, water supply, reduced chilling periods, and more rapid changes in the seasonal timing of crop development due to projected warming and extreme events.

Climate changes will increase stress on the region's rich diversity of plant and animal species. Widespread tree death

and fires, which already have caused billions of dollars in economic losses, are projected to increase, forcing wholesale changes to forest types, landscapes, and the communities that depend on them (see also Ch. 7: Forests).

Tourism and recreation, generated by the Southwest's winding canyons, snow-capped peaks, and Pacific Ocean beaches, provide a significant economic force that also faces climate change challenges. The recreational economy will be increasingly affected by reduced streamflow and a shorter snow season, influencing everything from the ski industry to lake and river recreation.

Observed and Projected Climate Change

The Southwest is already experiencing the impacts of climate change. The region has heated up markedly in recent decades, and the period since 1950 has been hotter than any comparably long period in at least 600 years (Ch. 2: Our Changing Climate, Key Message 3).[2,3,4] The decade 2001-2010 was the warmest in the 110-year instrumental record, with temperatures almost 2°F higher than historic averages, with fewer cold air outbreaks and more heat waves.[4] Compared to relatively uniform regional temperature increases, precipitation trends vary considerably across the region, with portions experiencing decreases and others experiencing increases (Ch. 2: Our Changing Climate, Key Message 5).[4] There is mounting evidence that the combination of human-caused temperature increases and recent drought has influenced widespread tree mortality,[6,7] increased fire occurrence and area burned,[8] and forest insect outbreaks (Ch. 7: Forests).[9] Human-caused temperature increases and drought have also caused earlier spring snowmelt and shifted runoff to earlier in the year.[10]

Regional annual average temperatures are projected to rise by 2.5°F to 5.5°F by 2041-2070 and by 5.5°F to 9.5°F by 2070-2099 with continued growth in global emissions (A2 emissions scenario), with the greatest increases in the summer and fall (Figure 20.1). If global emissions are substantially reduced (as in the B1 emissions scenario), projected temperature increases are 2.5°F to 4.5°F (2041-2070), and 3.5°F to 5.5°F (2070-2099). Summertime heat waves are projected to become longer and hotter, whereas the trend of decreasing wintertime cold air outbreaks is projected to continue (Ch. 2: Our Changing Climate, Key Message 7).[11,12] These changes will directly affect urban public health through increased risk of heat stress, and urban infrastructure through increased risk of disruptions to electric power generation.[13,14,15,16] Rising temperatures also have direct impacts on crop yields and productivity of key regional crops, such as fruit trees.

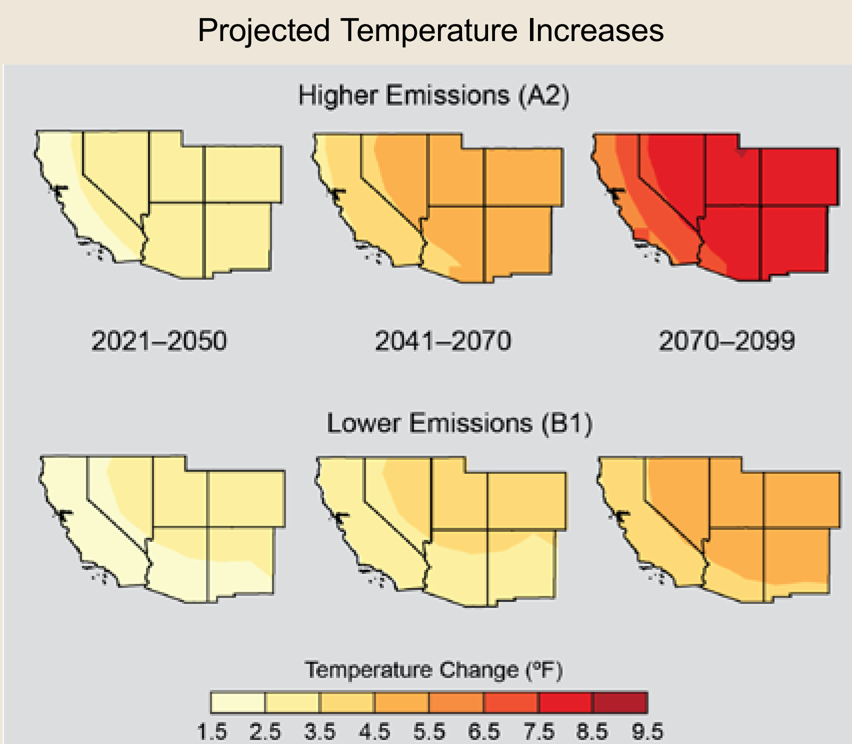

Figure 20.1. Maps show projected changes in average, as compared to 1971-1999. Top row shows projections assuming heat-trapping gas emissions continue to rise (A2). Bottom row shows projections assuming substantial reductions in emissions (B1). (Figure source: adapted from Kunkel et al. 2013[17]).

Projections of precipitation changes are less certain than those for temperature.[17,18] Under a continuation of current rising emissions trends (A2), reduced winter and spring precipitation is consistently projected for the southern part of the Southwest by 2100 as part of the general global precipitation reduction in subtropical areas. In the northern part of the region, projected winter and spring precipitation changes are smaller than natural variations. Summer and fall changes are also smaller than natural variations throughout the region (Ch. 2: Our Changing Climate, Key Message 5).[17] An increase in winter flood hazard risk in rivers is projected due to increases in flows of atmospheric moisture into California's coastal ranges and the Sierra Nevada (Ch. 3: Water).[19] These "atmospheric rivers" have contributed to the largest floods in California history[20] and can penetrate inland as far as Utah and New Mexico.

The Southwest is prone to drought. Southwest paleoclimate records show severe mega-droughts at least 50 years long.[21] Future droughts are projected to be substantially hotter, and for major river basins such as the Colorado River Basin, drought is projected to become more frequent, intense, and longer lasting than in the historical record.[18] These drought conditions present a huge challenge for regional management of water resources and natural hazards such as wildfire. In light of climate change and water resources treaties with Mexico, discussions will need to continue into the future to address demand pressures and vulnerabilities of groundwater and surface water systems that are shared along the border.

Vulnerabilities of Native Nations and Border Cities

The Southwest's 182 federally recognized tribes and communities in its U.S.-Mexico border region share particularly high vulnerabilities to climate changes such as high temperatures, drought, and severe storms. Tribes may face loss of traditional foods, medicines, and water supplies due to declining snowpack, increasing temperatures, and increasing drought (see also Ch 12: Indigenous Peoples).[22] Historic land settlements and high rates of poverty – more than double that of the general U.S. population[23] – constrain tribes' abilities to respond effectively to climate challenges.

Most of the Southwest border population is concentrated in eight pairs of fast-growing, adjacent cities on either side of the U.S.-Mexico border (like El Paso and Juárez) with shared problems. If the 24 U.S. counties along the entire border were aggregated as a 51st state, they would rank near the bottom in per capita income, employment rate, insurance coverage for children and adults, and high school completion.[24] Lack of financial resources and low tax bases for generating resources have resulted in a lack of roads and safe drinking water infrastructure, which makes it more daunting for tribes and border populations to address climate change issues. These economic pressures increase vulnerabilities to climate-related health and safety risks, such as air pollution, inadequate erosion and flood control, and insufficient safe drinking water.[25]

Key Message 1: Reduced Snowpack and Streamflows

Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems.

Winter snowpack, which slowly melts and releases water in spring and summer, when both natural ecosystems and people have the greatest needs for water, is key to the Southwest's hydrology and water supplies. Over the past 50 years across most of the Southwest, there has been less late-winter precipitation falling as snow, earlier snowmelt, and earlier arrival of most of the year's streamflow.[26,27] Streamflow totals in the Sacramento-San Joaquin, the Colorado, the Rio Grande, and in the Great Basin were 5% to 37% lower between 2001 and 2010 than the 20th century average flows.[4] Projections of further reduction of late-winter and spring snowpack and subsequent reductions in runoff and soil moisture[28,29] pose increased risks to the water supplies needed to maintain the Southwest's cities, agriculture, and ecosystems.

Temperature-driven reductions in snowpack are compounded by dust and soot accumulation on the surface of snowpack. This layer of dust and soot, transported by winds from lowland regions, increases the amount of the sun's energy absorbed by the snow. This leads to earlier snowmelt and evaporation – both of which have negative implications for water supply, alpine vegetation, and forests.[30,31] The prospect of more lowland soil drying out from drought and human disturbances (like agriculture and development) makes regional dust a potent future risk to snow and water supplies.

In California, drinking water infrastructure needs are estimated at $4.6 billion annually over the next 10 years, even without considering the effects of climate change.[32] Climate change will increase the cost of maintaining and improving drinking

Projected Snow Water Equivalent

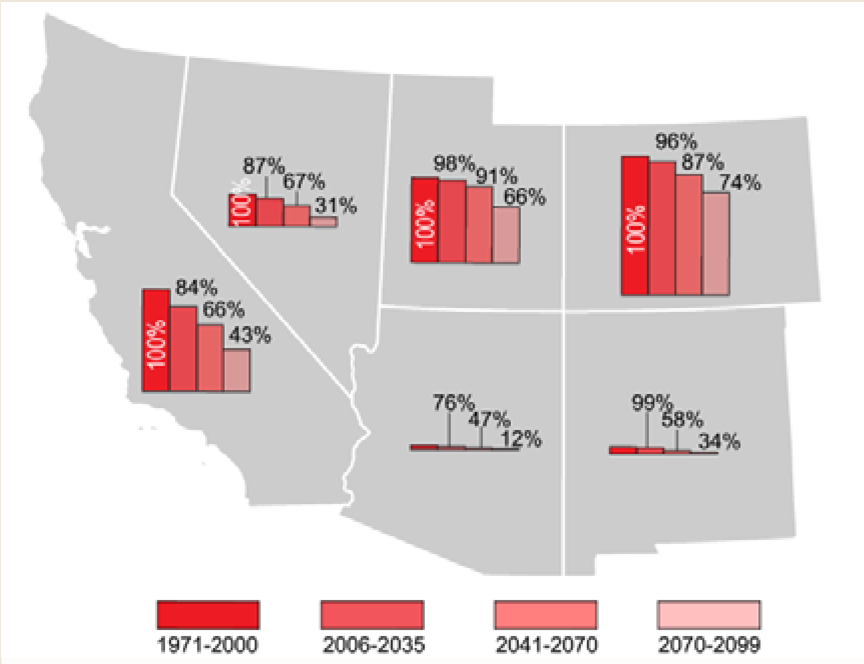

Figure 20.2. Snow water equivalent (SWE) refers to the amount of water held in a volume of snow, which depends on the density of the snow and other factors. Figure shows projected snow water equivalent for the Southwest, as a percentage of 1971-2000, assuming continued increases in global emissions (A2 scenario). The size of bars is in proportion to the amount of snow each state contributes to the regional total; thus, the bars for Arizona are much smaller than those for Colorado, which contributes the most to region-wide snowpack. Declines in peak SWE are strongly correlated with early timing of runoff and decreases in total runoff. For watersheds that depend on snowpack to provide the majority of the annual runoff, such as in the Sierra Nevada and in the Upper Colorado and Upper Rio Grande River Basins, lower SWE generally translates to reduced reservoir water storage. (Data from Scripps Institution of Oceanography).

water infrastructure, because expanded wastewater treatment and desalinating water for drinking are among the key strategies for supplementing water supplies.

Conservation efforts have proven to reduce water use, but are not projected to be sufficient if current trends for water supply and demand continue.[41] Large water utilities are currently attempting to understand how water supply and demand may change in conjunction with climate changes, and which adaptation options are most viable.[42,43]

The Southwest's Renewable Potential to Produce Energy with Less Water

The Southwest's abundant geothermal, wind, and solar power-generation resources could help transform the region's electric generating system into one that uses substantially more renewable energy. This transformation has already started, driven in part by renewable energy portfolio standards adopted by five of six Southwest states, and renewable energy goals in Utah. California's law limits imports of baseload electricity generation from coal and oil and mandates reduction of heat-trapping greenhouse gas emissions to 1990 levels by 2020.[33]

As the regional climate becomes hotter and, in parts of the Southwest, drier, there will be less water available for the cooling of thermal power plants (Ch. 2: Our Changing Climate),[34] which use about 40% of the surface water withdrawn in the United States.[35] The projected warming of water in rivers and lakes will reduce the capacity of thermal power plants, especially during summer when electricity demand skyrockets.[36] Wind and solar photovoltaic installations could substantially reduce water withdrawals. A large increase in the portion of power generated by renewable energy sources may be feasible at reasonable costs,[37,38] and could substantially reduce water withdrawals (Ch. 10: Energy, Water, and Land).[39]

Scenario for Greenhouse Gas Emissions Reductions in the Electricity Sector

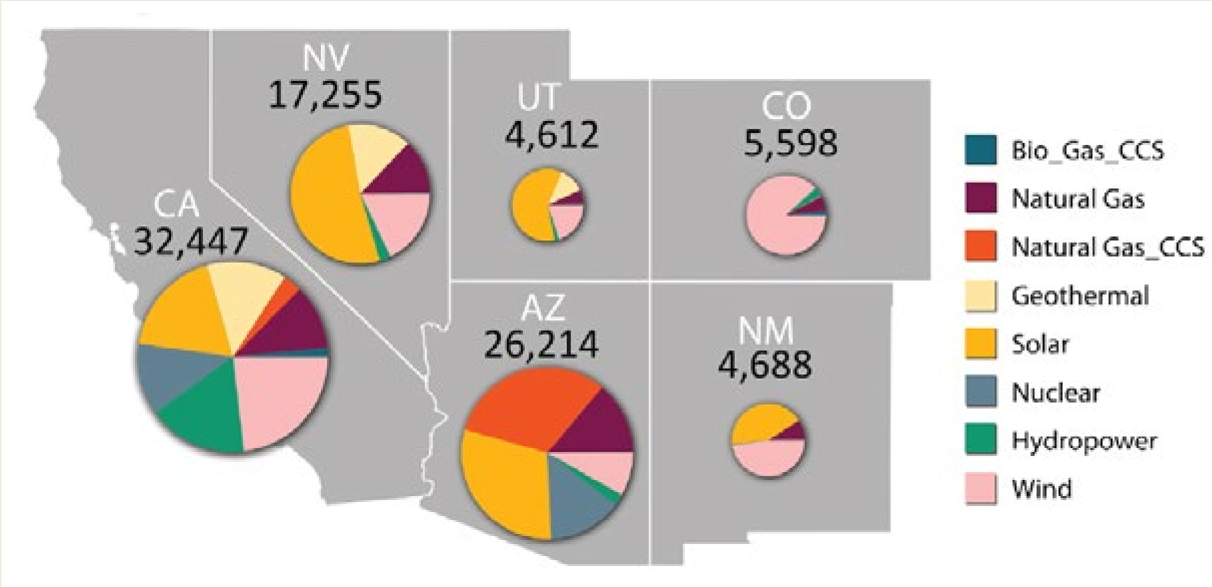

Figure 20.3. Major shifts in how electricity is produced can lead to large reductions in heat-trapping gas emissions. Shown is an illustrative scenario in which different energy combinations could, by 2050, achieve an 80% reduction of heat-trapping gas emissions from 1990 levels in the electricity sector in the Southwest. For each state, that mix varies, with the circle representing the average hourly generation in megawatts (the number above each circle) from 10 potential energy sources. CCS refers to carbon capture and storage. (Data from Wei et al. 2012, 2013[38,40]).

Key Message 2: Threats to Agriculture

The Southwest produces more than half of the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increasing temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.

Farmers are renowned for adapting to yearly changes in the weather, but climate change in the Southwest could happen faster and more extensively than farmers' ability to adapt. The region's pastures are rain-fed (non-irrigated) and highly susceptible to projected drought. Excluding Colorado, more than 92% of the region's cropland is irrigated, and agricultural uses account for 79% of all water withdrawals in the region.[44,45,46] A warmer, drier climate is projected to accelerate current trends of large transfers of irrigation water to urban areas,[47,48,49] which would affect local agriculturally dependent economies.

California produces about 95% of U.S. apricots, almonds, artichokes, figs, kiwis, raisins, olives, cling peaches, dried plums, persimmons, pistachios, olives, and walnuts, in addition to other high-value crops.[50] Drought and extreme weather affect the market value of fruits and vegetables more than other crops because they have high water content and because sales depend on good visual appearance.[51] The combination of a longer frost-free season, less frequent cold air outbreaks, and more frequent heat waves accelerates crop ripening and maturity, reduces yields of corn, tree fruit, and wine grapes, stresses livestock, and increases agricultural water consumption.[52,53] This combination of climate changes is projected to continue and intensify, possibly requiring a northward shift in crop production, displacing existing growers and affecting farming communities.[54,55]

Winter chill periods are projected to fall below the duration necessary for many California trees to bear nuts and fruits, which will result in lower yields.[56] Warm-season vegetable crops grown in Yolo County, one of California's biggest producers, may not be viable under hotter climate conditions.[54,57] Once temperatures increase beyond optimum growing thresholds, further increases in temperature, like those projected for the decades beyond 2050, can cause large decreases in crop yields and hurt the region's agricultural economy.

Longer Frost-Free Season Increases Stress on Crops

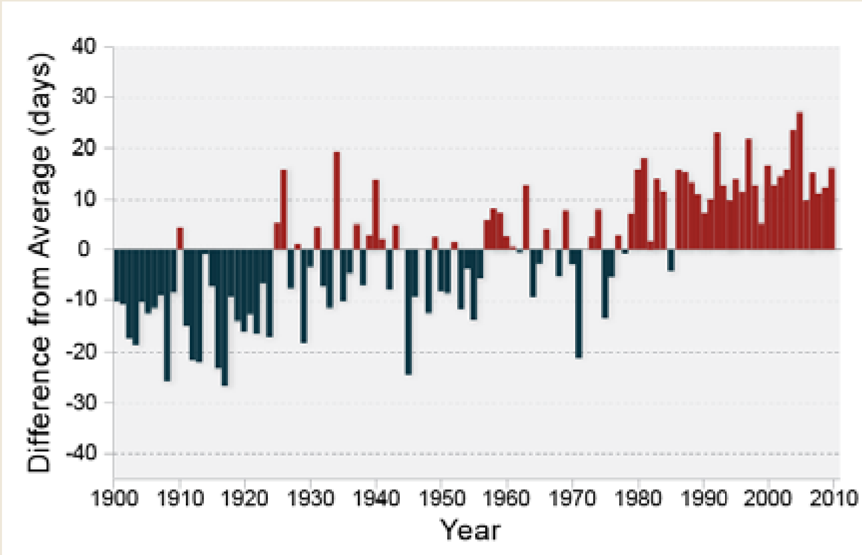

Figure 20.4. The frost-free season is defined as the period between the last occurrence of 32°F in spring and the first occurrence of 32°F in the subsequent fall. The chart shows significant increases in the number of consecutive frost-free days per year in the past three decades compared to the 1901-2010 average. Increased frost-free season length, especially in already hot and moisture-stressed regions like the Southwest, is projected to lead to further heat stress on plants and increased water demands for crops. Higher temperatures and more frost-free days during winter can lead to early bud burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring (see Ch. 6: Agriculture); in addition, with higher winter temperatures, some agricultural pests can persist year-round, and new pests and diseases may become established.[47] (Figure source: Hoerling et al. 2013[4]).

Key Message 3: Increased Wildfire

Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.

Fire naturally shapes southwestern landscapes. Indeed, many Southwest ecosystems depend on periodic wildfire to maintain healthy tree densities, enable seeds to germinate, and reduce pests.[58] Excessive wildfire destroys homes, exposes slopes to erosion and landslides, threatens public health, and causes economic damage.[59,60] The $1.2 billion in damages from the 2003 Grand Prix fire in southern California illustrates the high cost of wildfires.[60]

Beginning in the 1910s, the Federal Government developed a national policy of attempting to extinguish every fire, which allowed wood and other fuels to over-accumulate[61] and urban development to encroach on fire-prone areas. These changes have also contributed to increasing fire risk.

Increased warming due to climate change,[3] drought, insect infestations,[62] and accumulation of woody fuels and non-native grasses[63,64] make the Southwest vulnerable to increased wildfire. Climate outweighed other factors in determining burned area in the western U.S. from 1916 to 2003,[65] a finding confirmed by 3000-year long reconstructions of southwestern fire history.[66,67,68] Between 1970 and 2003, warmer and drier conditions increased burned area in western U.S. mid-elevation conifer forests by 650% (Ch. 7: Forests, Key Message 1).[8]

Drought and increased temperatures due to climate change have caused extensive tree death across the Southwest.[7,69] In addition, winter warming due to climate change has exacerbated bark beetle outbreaks by allowing more beetles, which normally die in cold weather, to survive and reproduce.[70] Wildfire and bark beetles killed trees across 20% of Arizona and New Mexico forests from 1984 to 2008.[62]

Numerous fire models project more wildfire as climate change continues.[64,71,72,73,74] Models project a doubling of burned area in the southern Rockies,[73] and up to a 74% increase in burned area in California,[74] with northern California potentially experiencing a doubling under a high emissions scenario toward the end of the century. Fire contributes to upslope shifting of vegetation, spread of invasive plants after extensive and intense fire, and conversion of forests to woodland or grassland.[63,75]

Historical and projected climate change makes two-fifths (40%) of the region vulnerable to these shifts of major vegetation types or biomes; notably threatened are the conifer forests of southern California and sky islands of Arizona.[71]

Prescribed burning, mechanical thinning, and retention of large trees can help some southwestern forest ecosystems adapt to climate change.[68,76] These adaptation measures also reduce emissions of the gases that cause climate change because long-term storage of carbon in large trees can outweigh short-term emissions from prescribed burning.[61,77]

Key Message 4: Sea Level Rise and Coastal Damage

Flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some California coastal areas during storms and extreme high tides. Sea level rise is projected to increase as Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher seas and reach farther inland.

In the last 100 years, sea level has risen along the California coast by 6.7 to 7.9 inches.[78] In the last decade, high tides on top of this sea level rise have contributed to new damage to infrastructure, such as the inundation of Highway 101 near San Francisco and backup of seawater into the San Francisco Bay Area sewage systems.

Although sea level along the California coast has been relatively constant since 1980, both global and relative Southwest sea levels are expected to increase at accelerated rates.[78,79,80] During the next 30 years, the greatest impacts will be seen during high tides and storm events. Rising sea level will allow more wave energy to reach farther inland and extend high tide periods, worsening coastal erosion on bluffs and beaches and increasing flooding potential.[18,81,82,83,84]

The result will be impacts to the nation's largest ocean-based economy, which is estimated at $46 billion annually.[85,86] If adaptive action is not taken, coastal highways, bridges, and other transportation infrastructure (such as the San Francisco and Oakland airports) are at increased risk of flooding with a 16-inch rise in sea level in the next 50 years,[5] an amount consistent with the 1 to 4 feet of expected global increase in sea level (see Ch. 2: Our Changing Climate, Key Message 10). In Los Angeles, sea level rise poses a threat to groundwater supplies and estuaries,[82,87] by potentially contaminating groundwater with seawater, or increasing the costs to protect coastal freshwater aquifers.[88]

Projected increases in extreme coastal flooding as a result of sea level rise will increase human vulnerability to coastal flooding events. Currently, 260,000 people in California are at risk from what is considered a once-in-100-year flood.[82] With a sea level rise of about three feet (in the range of projections for this century – Ch. 2: Our Changing Climate, Key Message 10)[78,80] and at current population densities, 420,000 people would be at risk from the same kind of 100-year flood event,[85] based on existing exposure levels. Highly vulnerable populations

Coastal Risks Posed by Sea Level Rise and High Tides

Figure 20.5. King tides, which typically happen twice a year as a result of a gravitational alignment of the sun, moon, and Earth, provide a preview of the risks rising sea levels may present along California coasts in the future. While king tides are the extreme high tides today, with projected future sea level rise, this level of water and flooding will occur during regular monthly high tides. During storms and future king tides, more coastal flooding and damage will occur. The King Tide Photo Initiative encourages the public to visually document the impact of rising waters on the California coast, as exemplified during current king tide events. Photos show water levels along the Embarcadero in San Francisco, California during relatively normal tides (top), and during an extreme high tide or "king tide" (bottom). (Photo credit: Mark Johnsson).

– people less able to prepare, respond, or recover from natural disaster due to age, race, or income – make up approximately 18% of the at-risk population (Ch. 25: Coasts).[85,89]

The California state government, through its Ocean and Coastal Resources Adaptation Strategy, along with local governments, is using new sea level mapping and information about social vulnerability to undertake coastal adaptation planning. NOAA has created an interactive map showing areas that would be affected by sea level rise (http://www.csc.noaa.gov/slr/viewer/#).

Key Message 5: Heat Threats to Health

Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.

The Southwest has the highest percentage of its population living in cities of any U.S. region. Its urban population rate, 92.7%, is 12% greater than the national average.[90] Increasing metropolitan populations already pose challenges to providing adequate domestic water supplies, and the combination of increased population growth and projected increased risks to surface water supplies will add further challenges.[91,92] Tradeoffs are inevitable between conserving water to help meet the demands of an increasing population and providing adequate water for urban greenery to reduce increasing urban temperatures.

Urban infrastructures are especially vulnerable because of their interdependencies; strains in one system can cause disruptions in another (Ch. 11: Urban, Key Message 2; Ch. 9: Human Health).[16,93] For example, an 11-minute power system disturbance in September 2011 cascaded into outages that left 1.5 million San Diego residents without power for 12 hours;[94] the outage disrupted pumps and water service, causing 1.9 million gallons of sewage to spill near beaches.[95] Extensive use of air conditioning to deal with high temperatures can quickly increase electricity demand and trigger cascading energy system failures, resulting in blackouts or brownouts.[14,15]

Urban Heat and Public Health

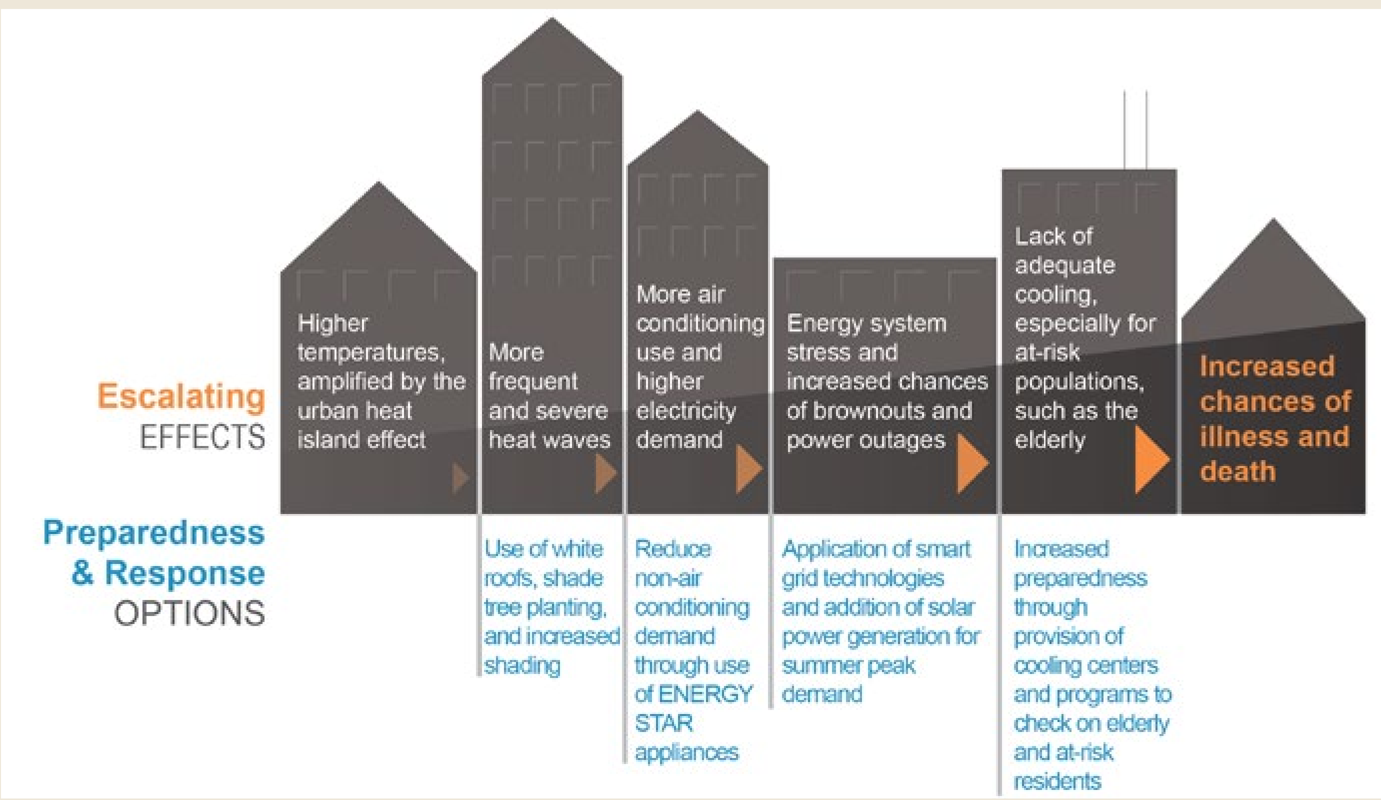

Figure 20.6. The projected increase in heat waves in Southwest cities (Ch. 2: Our Changing Climate, Key Message 7) increases the chances that a chain of escalating effects could lead to serious increases in illness and death due to heat stress. The top of the figure provides some of the links in that chain, while the bottom of the figure provides adaptation and improved governance options that can reduce this vulnerability and improve the resilience of urban infrastructure and community residents.

Heat stress, a recurrent health problem for urban residents, has been the leading weather-related cause of death in the United States since 1986, when record keeping began[96] – and the highest rates nationally are found in Arizona.[97] The effects of heat stress are greatest during heat waves lasting several days or more, and heat waves are projected to increase in frequency, duration, and intensity,[11,13,98] become more humid,[11] and cause a greater number of deaths.[99] Already, severe heat waves, such as the 2006 ten-day California event, have resulted in high mortality, especially among elderly populations.[100] In addition, evidence indicates a greater likelihood of impacts in less affluent neighborhoods, which typically lack shade trees and other greenery and have reduced access to air conditioning.[101]

Exposure to excessive heat can also aggravate existing human health conditions, like for those who suffer from respiratory or heart disease.[99] Increased temperatures can reduce air quality, because atmospheric chemical reactions proceed faster in warmer conditions. The outcome is that heat waves are often accompanied by increased ground-level ozone,[102] which can cause respiratory distress. Increased temperatures and longer warm seasons will also lead to shifts in the distribution of disease-transmitting mosquitoes (Ch. 9: Human Health, Key Message 1).[97]

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was the Southwest Regional Climate assessment workshop that was held August 1-4, 2011, in Denver, CO with more than 80 participants in a series of scoping presentations and workshops. The workshop began the process leading to a foundational Technical Input Report (TIR) report.[103] The TIR consists of nearly 800 pages organized into 20 chapters that were assembled by 122 authors representing a wide range of inputs, including governmental agencies, non-governmental organizations, tribes, and other entities. The report findings were described in a town hall meeting at the American Geophysical Union's annual fall meeting in 2011, and feedback was collected and incorporated into the draft.

The chapter author team engaged in multiple technical discussions through more than 15 biweekly teleconferences that permitted a careful review of the foundational TIR[103] and of approximately 125 additional technical inputs provided by the public, as well as the other published literature and professional judgment. The chapter author team then met at the University of Southern California on March 27-28, 2012, for expert deliberation of draft key messages by the authors. Each key message was defended before the entire author team prior to the key message being selected for inclusion. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities, which include magnitude, timing, persistence and reversibility, likelihood and confidence, potential for adaptation, distribution, and importance of the vulnerable system."[104]

Key message #1 Traceable Account

Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems.

Description of evidence base

The key message was chosen based on input from the extensive evidence documented in the Southwest Technical Input Report[103] and additional technical input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Key Message 5 in Chapter 2, Our Changing Climate, also provides evidence for declining precipitation across the United States, and a regional study[17] discusses regional trends and scenarios for the Southwest.

Over the past 50 years, there has been a reduction in the amount of snow measured on April 1 as a proportion of the precipitation falling in the corresponding water-year (October to September), which affects the timing of snowfed rivers. The implication of this finding is that the lower the proportion of April 1 snow water equivalent in the water-year-to-date precipitation, the more rapid the runoff, and the earlier the timing of center-of-mass of streamflow in snowfed rivers.[26,27] For the "recent decade" (2001 to 2010), snowpack evidence is from U.S. Department of Agriculture (USDA) Natural Resources Conservation Service snow course data, updated through 2010. One study[4] has analyzed streamflow amounts for the region's four major river basins, the Colorado, Sacramento-San Joaquin, Great Basin (Humboldt River, NV), and the Rio Grande; data are from the U.S. Department of the Interior – Bureau of Reclamation, California Department of Water Resources, U.S. Geological Survey, and the International Boundary and Water Commission (U.S. Section), respectively. These data are backed by a rigorous detection and attribution study.[10] Projected trends[18] make use of downscaled climate parameters for 16 global climate models (GCMs), and hydrologic projections for the Colorado River, Rio Grande, and Sacramento-San Joaquin River System.

Based on GCM projections, downscaled and run through the variable infiltration capacity (VIC) hydrological model,[105] there are projected reductions in spring snow accumulation and total annual runoff, leading to reduced surface water supply reliability for much of the Southwest, with greater impacts occurring during the second half of this century.[18,28]

Future flows in the four major Southwest rivers are projected to decline as a result of a combination of increased temperatures, increased evaporation, less snow, and less persistent snowpack. These changes have been projected to result in decreased surface water supplies, which will have impacts for allocation of water resources to major uses, such as urban drinking water, agriculture, and ecosystem flows.

New information and remaining uncertainties

Different model simulations predict different levels of snow loss. These differences arise because of uncertainty in climate change warming and precipitation projections due to differences among GCMs, uncertainty in regional downscaling, uncertainty in hydrological modeling, differences in emissions, aerosols, and other forcings, and because differences in the hemispheric and regional-scale atmospheric circulation patterns produced by different GCMs produce different levels of snow loss in different model simulations.

In addition to the aforementioned uncertainties in regional climate and hydrology projections, projection of future surface water supply reliability includes at least the following additional uncertainties: 1) changes in water management, which depend on agency resources and leadership and cooperation of review boards and the public;[106] 2) management responses to non-stationarity;[107] 3) legal, economic, and institutional options for augmenting existing water supplies, adding underground water storage and recovery infrastructure, and fostering further water conservation (for example, Udall 2013[108]); 4) adjudication of unresolved water rights; and 5) local, state, regional, and national policies related to the balance of agricultural, ecosystem, and urban water use (for example, Reclamation 2011[43]).

Assessment of confidence based on evidence

There is **high** confidence in the continued trend of declining snowpack and streamflow in parts of the Southwest given the evidence base and remaining uncertainties.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

For the impacts on water supply, there is **high** confidence that reduced surface water supply reliability will affect the region's cities, agriculture, and ecosystems.

Key message #2 Traceable Account

The Southwest produces more than half of the nation's high-value specialty crops, which are irrigation-dependent and particularly vulnerable to extremes of moisture, cold, and heat. Reduced yields from increasing temperatures and increasing competition for scarce water supplies will displace jobs in some rural communities.

Description of evidence base

Increased competition for scarce water was presented in the first key message and in the foundational Technical Input Report (TIR).[103] U.S. temperatures, including those for the Southwest region, have increased and are expected to continue to rise (Ch. 2: Our Changing Climate, Key Message 3). Heat waves have become more frequent and intense and droughts are expected to become more intense in the Southwest (Ch. 2: Our Changing Climate, Key Message 7). The length of the frost-free season in the Southwest has been increasing, and frost-free season length is projected to increase (Ch. 2: Our Changing Climate, Key Message 4). A regional study[17] discusses the trends and scenarios in the Southwest for moisture, cold, heat, and their extremes.

There is abundant evidence of irrigation dependence and vulnerability of high-value specialty crops to extremes of moisture, cold, and heat, including, prominently, the 2009 National Climate Assessment[109] and the foundational TIR.[103] Southwest agricultural production statistics and irrigation dependence of that production is delineated in the USDA 2007 Census of Agriculture[45] and the USDA Farm and Ranch Irrigation Survey.[46]

Reduced Yields. Even under the most conservative emissions scenarios evaluated (the combination of SRES B1emissions scenario with statistically downscaled winter chill projections from the HADCM3 climate model), one study[56] projected that required winter chill periods will fall below the number of hours that are necessary for many of the nut- and fruit-bearing trees of California, and yields are projected to decline as a result. A second study[54] found that California wheat acreage and walnut acreage will decline due to increased temperatures. Drought and extreme weather may have more effect on the market value of fruits and vegetables, as opposed to other crops, because fruits and vegetables have high water content and because consumers expect good visual appearance and flavor.[51] Extreme daytime and nighttime temperatures have been shown to accelerate crop ripening and maturity, reduce yield of crops such as corn, fruit trees, and vineyards, cause livestock to be stressed, and increase water consumption in agriculture.[53]

Irrigation water transfers to urban. Warmer, drier future scenarios portend large transfers of irrigation water to urban areas even though agriculture will need additional water to meet crop demands, affecting local agriculturally-dependent economies.[55] In particular areas of the Southwest (most notably lower-central Arizona), a significant reduction in irrigated agriculture is already underway as land conversion occurs near urban centers.[48] Functioning water markets, which may require legal and institutional changes, can enable such transfers and reduce the social and economic impacts of water shortages to urban areas.[47] The economic impacts of climate change on Southwest fruit and nut growers are projected to be substantial and will result in a northward shift in production of these crops, displacing growers and affecting communities.

New information and remaining uncertainties

Competition for water is an uncertainty. The extent to which water transfers take place depends on whether complementary investments in conveyance or storage infrastructure are made. Currently, there are legal and institutional restrictions limiting water transfers across state and local jurisdictions. It is uncertain whether infrastructure investments will be made or whether institutional innovations facilitating transfers will develop. Institutional barriers will be greater if negative third-party effects of transfers are not adequately addressed. Research that would improve the information base to inform future water transfer debates includes: 1) estimates of third party impacts, 2) assessment of institutional mechanisms to reduce those impacts, 3) environmental impacts of water infrastructure projects, and 4) options and costs of mitigating those environmental impacts.

Extremes and phenology. A key uncertainty is the timing of extreme events during the phenological stage of the plant or the growth cycle of the animal. For example, plants are more sensitive to extreme high temperatures and drought during the pollination stage compared to vegetative growth stages.

Genetic improvement potential. Crop and livestock reduction studies by necessity depend on assumptions about adaptive actions by farmers and ranchers. However, agriculture has proven to be highly adaptive in the past. A particularly high uncertainty is the ability of conventional breeding and biotechnology to keep pace with the crop plant and animal genetic improvements needed for adaptation to climate-induced biotic and abiotic stresses.

Assessment of confidence based on evidence

Although evidence includes studies of observed climate and weather impacts on agriculture, projections of future changes using climate and crop yield models and econometric models show varying results depending on the choice of crop and assumptions regarding water availability. For example, projections of 2050 California crop yields show reductions in field crop yields, based on assumptions of a 21% decline in agricultural water use, shifts away from water-intensive crops to high-value specialty crops, and development of a more economical means of transferring water from northern to southern California.[47] Other studies, using projections of a dry, warmer future for California, and an assumption that water will flow from lower- to higher-valued uses (such as urban water use), generated a 15% decrease in irrigated acreage and a shift from lower- to higher-valued crops.[49]

Because net reductions in the costs of water shortages depend on multiple institutional responses, it is difficult as yet to locate a best estimate of water transfers between zero and the upper bound. Water scarcity may also be a function of tradeoffs between economic returns from agricultural production and returns for selling off property or selling water to urban areas (for example, Imperial Valley transfers to San Diego).

Given the evidence base and remaining uncertainties, confidence is **high** in this key message.

Key Message #3 Traceable Account

Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.

Description of evidence base

Increased warming and drought are extensively described in the foundational Technical Input Report (TIR).[103] U.S. temperatures have increased and are expected to continue to rise (Ch. 2: Our Changing Climate, Key Message 3). There have been regional changes in droughts, and there are observed and projected changes in cold and heat waves and droughts (Ch. 2: Our Changing Climate, Key Message 7) for the nation. A study for the Southwest[17] discusses trends and scenarios in both cold waves and heat waves.

Analyses of weather station data from the Southwest have detected changes from 1950 to 2005 that favor wildfire, and statistical analyses have attributed the changes to anthropogenic climate change. The changes include increased temperatures,[3] reduced snowpack,[27] earlier spring warmth,[30] and streamflow.[10] These climate changes have increased background tree mortality rates from 1955 to 2007 in old-growth conifer forests in California, Colorado, Utah, and the northwestern states[7] and caused extensive piñon pine mortality in Arizona, Colorado, New Mexico, and Utah between 1989 and 2003.[69]

Climate factors contributed to increases in wildfire in the previous century. In mid-elevation conifer forests of the western United States, increases in spring and summer temperatures, earlier snowmelt, and longer summers increased fire frequency by 400% and burned area by 650% from 1970 to 2003.[8] Multivariate analysis of wildfire across the western U.S. from 1916 to 2003 indicates that climate was the dominant factor controlling burned area, even during periods of human fire suppression.[65] Reconstruction of fires of the past 400 to 3000 years in the western U.S.[66] and in Yosemite and Sequoia National Parks in California[67,68] confirm that temperature and drought are the dominant factors explaining fire occurrence.

Four different fire models project increases in fire frequency across extensive areas of the Southwest in this century.[71,72,73,74] Multivariate statistical generalized additive models[64,72] project extensive increases across the Southwest, but the models project decreases when assuming that climate alters patterns of net primary productivity. Logistic regressions[74] project increases across most of California, except for some southern parts of the state, with average fire frequency increasing 37% to 74%. Linear regression models project up to a doubling of burned area in the southern Rockies by 2070 under emissions scenarios B1 or A2.[73] The MC1 dynamic global vegetation model projects increases in fire frequencies on 40% of the area of the Southwest from 2000 to 2100 and decreases on 50% of the areas for emissions scenarios B1 and A2.[71]

Excessive wildfire destroys homes, exposes slopes to erosion and landslides, and threatens public health, causing economic damage.[59,60] Further impacts to communities and various economies (local, state, and national) have been projected.[74]

New information and remaining uncertainties

Uncertainties in future projections derive from the inability of models to accurately simulate all past fire patterns, and from the different GCMs, emissions scenarios, and spatial resolutions used by different fire model projections. Fire projections depend highly on the spatial and temporal distributions of precipitation projections, which vary widely across GCMs. Although models generally project future increases in wildfire, uncertainty remains on the exact locations. Research groups continue to refine the fire models.

Assessment of confidence based on evidence

There is **high** confidence in this key message given the extensive evidence base and discussed uncertainties.

Key message #4 Traceable Account

Flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some California coastal areas during storms and extreme high tides. Sea level rise is projected to increase as Earth continues to warm, resulting in major damage as wind-driven waves ride upon higher seas and reach farther inland.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report.[103] Several studies document potential coastal flooding, erosion, and wind-driven wave damages in coastal areas of California due to sea level rise (for example, Bromirski et al. 2012; Heberger et al. 2011, and Revell et al. 2011[81,82]). Global sea level has risen, and further rise of 1 to 4 feet is projected by 2100 (Ch. 2: Our Changing Climate, Key Message 10).

All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. In addition, numerous recent studies[78,80] produce much higher sea level rise projections for the rest of this century as compared to the projections in the most recent report of the Intergovernmental Panel on Climate Change[83] for the rest of this century.

New information and remaining uncertainties

There is strong recent evidence from satellites such as GRACE[110] and from direct observations that glaciers and ice caps worldwide are losing mass relatively rapidly, contributing to the recent increase in the observed rate of sea level rise.

Major uncertainties are associated with sea level rise projections, such as the behavior of ice sheets with global warming and the actual level of global warming that the Earth will experience in the future.[78,80] Regional sea level rise projections are even more uncertain than the projections for global averages because local factors such as the steric component (changes in the volume of water with changes in temperature and salinity) of sea level rise at regional levels and the vertical movement of land have large uncertainties.[78] However, it is virtually certain that sea levels will go up with a warming planet as demonstrated in the paleoclimatic record, modeling, and from basic physical arguments.

Assessment of confidence based on evidence

Given the evidence, especially since the last IPCC report,[83] there is **very high** confidence the sea level will continue to rise and that this will entail major damage to coastal regions in the Southwest. There is also **very high** confidence that flooding and erosion in coastal areas are already occurring even at existing sea levels and damaging some areas of the California coast during storms and extreme high tides.

Key message #5 Traceable Account

Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.

Description of evidence base

There is excellent agreement regarding the urban heat island effect and exacerbation of heat island temperatures by increases in regional temperatures caused by climate change. There is abundant evidence of urban heat island effect for some Southwest cities (for example, Sheridan et al.[98]), as well as several studies, some from outside the region, of the public health threats of urban heat to residents (for example, Ch. 9: Human Health, Ostro et al. 2009, 2001[99,100]). Evidence includes observed urban heat island studies and modeling of future climates, including some climate change modeling studies for individual urban areas (for example, Phoenix and Los Angeles). There is wide agreement in Southwest states that increasing temperatures combined with projected population growth will stress urban water supplies and require continued water conservation and investment in new water supply options. There is substantial agreement that disruption to urban electricity may cause cascading impacts, such as loss of water, and that projected diminished supplies will pose challenges for urban cooling (for example, the need for supplemental irrigation for vegetation-based cooling). However, there are no studies on urban power disruption induced by climate change.

With projected surface water losses, and increasing water demand due to increasing temperatures and population, water supply in Southwest cities will require greater conservation efforts and capital investment in new water supply sources.[92] Several southwestern states, including California, New Mexico, and Colorado have begun to study climate impacts to water resources, including impacts in urban areas.[91]

The interdependence of infrastructure systems is well established, especially the dependence of systems on electricity and communications and control infrastructures, and the potential cascading effects of breakdowns in infrastructure systems.[16] The concentration of infrastructures in urban areas adds to the vulnerability of urban populations to infrastructure breakdowns. This has been documented in descriptions for major power outages such as the Northeast power blackout of 2003, or the recent September 2011 San Diego blackout.[94]

A few references point to the role of urban power outages in threatening public health due to loss of air conditioning[14] and disruption to water supplies.[94]

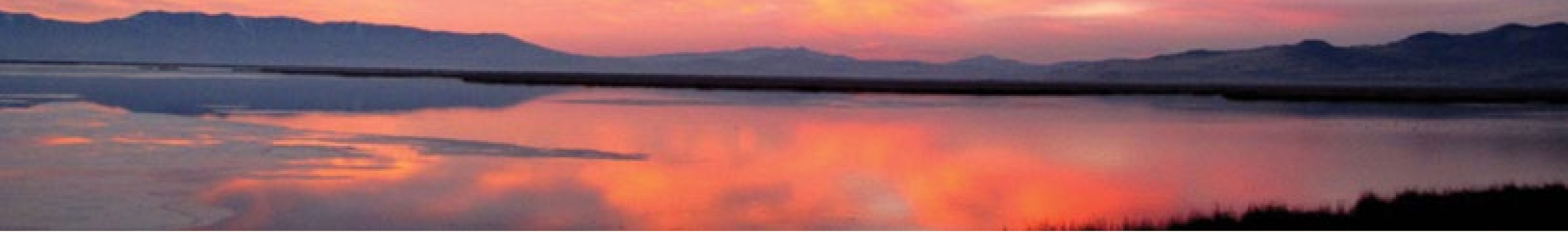
New information and remaining uncertainties

Key uncertainties include the intensity and spatial extent of drought and heat waves. Uncertainty is also associated with quantification of the impact of temperature and water availability on energy generation, transmission, distribution, and consumption – all of which have an impact on possible disruptions to urban electricity. Major disruptions are contingent on a lack of operator response and/or adaptive actions such as installation of adequate electricity-generating capacity to serve the expected enhanced peak electricity demand. Thus a further uncertainty is the extent to which adaptation actions are taken.

Assessment of confidence based on evidence

The urban heat island effect is well demonstrated and hence projected climate-induced increases to heat will increase exposure to heat-related illness. Electricity disruptions are a key uncertain factor, and potential reductions in water supply not only may reduce hydropower generation, but also availability of water for cooling of thermal power plants.

Based on the substantial evidence and the remaining uncertainties, confidence in each aspect of the key message is **high**.



Climate Change Impacts in the United States

CHAPTER 21
NORTHWEST

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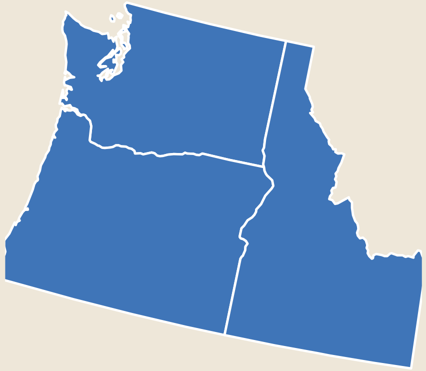

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

21 NORTHWEST

Key Messages

1. **Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.**
2. **In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.**
3. **The combined impacts of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.**
4. **While the agriculture sector's technical ability to adapt to changing conditions can offset some adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.**

With craggy shorelines, volcanic mountains, and high sage deserts, the Northwest's complex and varied topography contributes to the region's rich climatic, geographic, social, and ecologic diversity. Abundant natural resources – timber, fisheries, productive soils, and plentiful water – remain important to the region's economy.

Snow accumulates in mountains, melting in spring to power both the region's rivers and economy, creating enough hydropower (40% of national total)[1] to export 2 to 6 million megawatt hours per month.[2] Snowmelt waters crops in the dry interior, helping the region produce tree fruit (number one in the world) and almost $17 billion worth of agricultural commodities, including 55% of potato, 15% of wheat, and 11% of milk production in the United States.[3]

Seasonal water patterns shape the life cycles of the region's flora and fauna, including iconic salmon and steelhead, and forested ecosystems, which cover 47% of the landscape.[4] Along more than 4,400 miles of coastline, regional economic centers are juxtaposed with diverse habitats and ecosystems that support thousands of species of fish and wildlife, including commercial fish and shellfish resources valued at $480 million in 2011.[5]

Adding to the influence of climate, human activities have altered natural habitats, threatened species, and extracted so much water that there are already conflicts among multiple users in dry years. More recently, efforts have multiplied to balance environmental restoration and economic growth while evaluating climate risks. As conflicts and tradeoffs increase, the region's population continues to grow, and the regional consequences of climate change continue to unfold. The need to seek solutions to these conflicts is becoming increasingly urgent.

The Northwest's economy, infrastructure, natural systems, public health, and vitally important agriculture sector all face important climate change related risks. Those risks – and possible adaptive responses – will vary significantly across the region.[6] Impacts on infrastructure, natural systems, human health, and economic sectors, combined with issues of social and ecological vulnerability, will play out quite differently in largely natural areas, like the Cascade Range or Crater Lake National Park, than in urban areas like Seattle and Portland (Ch. 11: Urban),[7] or among the region's many Native American tribes, like the Umatilla or the Quinault (Ch. 12: Indigenous Peoples).[8]

As climatic conditions diverge from those that determined patterns of development and resource use in the last century, and as demographic, economic, and technological changes also stress local systems, efforts to cope with climate change would benefit from an evolving, iterative risk management approach.[9]

Observed Climate Change

Temperatures increased across the region from 1895 to 2011, with a regionally averaged warming of about 1.3°F.[10] While precipitation has generally increased, trends are small as compared to natural variability. Both increasing and decreasing trends are observed among various locations, seasons, and time periods of analysis (Ch. 2: Our Changing Climate, Figure 2.12). Studies of observed changes in extreme precipitation use different time periods and definitions of "extreme," but none find statistically significant changes in the Northwest.[11] These and other climate trends include contributions from both human influences (chiefly heat-trapping gas emissions) and natural climate variability, and consequently are not projected to be uniform or smooth across the country or over time (Ch. 2: Our Changing Climate, Key Message 3). They are also consistent with expected changes due to human activities (Ch. 2: Our Changing Climate, Key Message 1).

Projected Climate Change

An increase in average annual temperature of 3.3°F to 9.7°F is projected by 2070 to 2099 (compared to the period 1970 to 1999), depending largely on total global emissions of heat-trapping gases. The increases are projected to be largest in summer. This chapter examines a range of scenarios, including ones where emissions increase and then decline, leading to lower (B1 and RCP 4.5) and medium (A1B) total emissions, and scenarios where emissions continue to rise with higher totals (A2, A1FI, and RCP 8.5 scenarios). Change in annual average precipitation in the Northwest is projected to be within a range of an 11% decrease to a 12% increase for 2030 to 2059 and a 10% decrease to an 18% increase for 2070 to 2099[12] for the B1, A1B, and A2 scenarios (Ch. 2: Our Changing Climate). For every season, some models project decreases and some project increases (Ch. 2: Our Changing Climate, Key Message 5),[10,12] yet one aspect of seasonal changes in precipitation is largely consistent across climate models: for scenarios of continued growth in global heat-trapping gas emissions, summer precipitation is projected to decrease by as much as 30% by the end of the century (Ch. 2: Our Changing Climate).[10,12] Northwest summers are already dry and although a 10% reduction (the average projected change for summer) is a small amount of precipitation, unusually dry summers have many noticeable consequences, including low streamflow west of the Cascades[13] and greater extent of wildfires throughout the region.[14] Note that while projected temperature increases are large relative to natural variability, the relatively small projected changes in precipitation are likely to be masked by natural variability for much of the century.[15]

Ongoing research on the implications of these and other changes largely confirms projections and analyses made over the last decade, while providing more information about how climate impacts are likely to vary from place to place within the region. In addition, new areas of concern, such as ocean acidification, have arisen.

Key Message 1: Water-related Challenges

Changes in the timing of streamflow related to changing snowmelt have been observed and will continue, reducing the supply of water for many competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of Observed and Projected Changes

Observed regional warming has been linked to changes in the timing and amount of water availability in basins with significant snowmelt contributions to streamflow. Since around 1950, area-averaged snowpack on April 1 in the Cascade Mountains decreased about 20%,[16] spring snowmelt occurred 0 to 30 days earlier depending on location,[17] late winter/early spring streamflow increases ranged from 0% to greater than 20% as a fraction of annual flow,[18,19] and summer flow decreased 0% to 15% as a fraction of annual flow,[17] with exceptions in smaller areas and shorter time periods.[20]


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Hydrologic response to climate change will depend upon the dominant form of precipitation in a particular watershed, as well as other local characteristics including elevation, aspect, geology, vegetation, and changing land use.[22] The largest responses are expected to occur in basins with significant snow accumulation, where warming increases winter flows and advances the timing of spring melt.[18,23] By 2050, snowmelt is projected to shift three to four weeks earlier than the 20th century average, and summer flows are projected to be substantially lower, even for an emissions scenario that assumes substantial emissions reductions (B1).[24] In some North Cascade rivers, a significant fraction (10% to 30%) of late summer flow originates as glacier melt;[25] the consequences of eventual glacial disappearance are not well quantified. Basins with a significant groundwater component may be less responsive to climate change than indicated here.[26]

Changes in river-related flood risk depends on many factors, but warming is projected to increase flood risk the most in mixed basins (those with both winter rainfall and late spring snowmelt-related runoff peaks) and remain largely unchanged in snow-dominant basins.[27] Regional climate models project increases of 0% to 20% in extreme daily precipitation, depending on location and definition of "extreme" (for example, annual wettest day).

Observed Shifts in Streamflow Timing

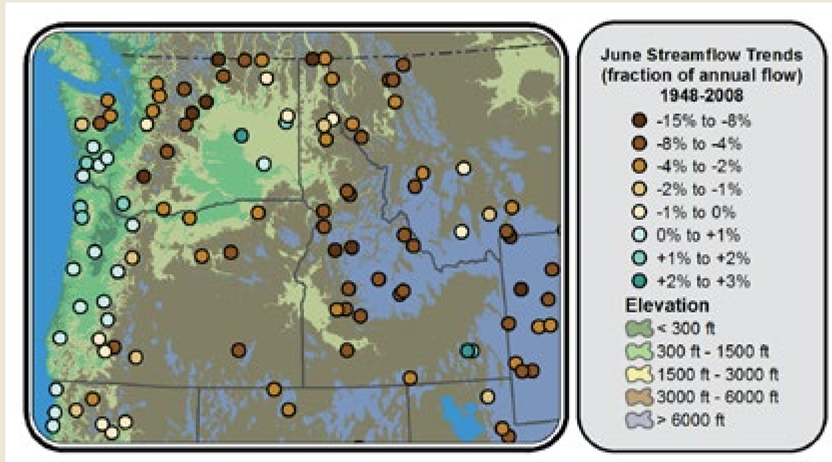

Figure 21.1. Reduced June flows in many Northwest snow-fed rivers is a signature of warming in basins that have a significant snowmelt contribution. The fraction of annual flow occurring in June increased slightly in rain-dominated coastal basins and decreased in mixed rain-snow basins and snowmelt-dominated basins over the period 1948 to 2008.[21] The high flow period is in June for most Northwest river basins; decreases in summer flows can make it more difficult to meet a variety of competing human and natural demands for water. (Figure source: adapted from Fritze et al. 2011[21]).

Future Shift in Timing of Stream Flows

Reduced Summer Flows

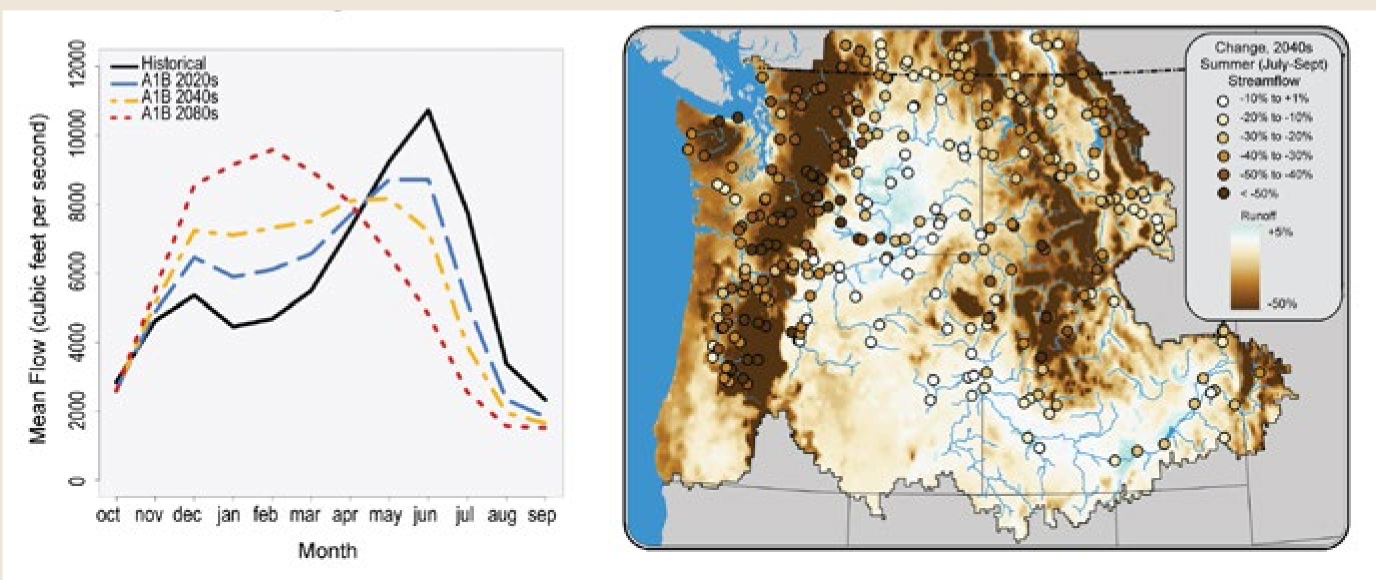

Figure 21.2. (Left) Projected increased winter flows and decreased summer flows in many Northwest rivers will cause widespread impacts. Mixed rain-snow watersheds, such as the Yakima River basin, an important agricultural area in eastern Washington, will see increased winter flows, earlier spring peak flows, and decreased summer flows in a warming climate. Changes in average monthly streamflow by the 2020s, 2040s, and 2080s (as compared to the period 1916 to 2006) indicate that the Yakima River basin could change from a snow-dominant to a rain-dominant basin by the 2080s under the A1B emissions scenario (with eventual reductions from current rising emissions trends). (Figure source: adapted from Elsner et al. 2010)[24].

(Right) Natural surface water availability during the already dry late summer period is projected to decrease across most of the Northwest. The map shows projected changes in local runoff (shading) and streamflow (colored circles) for the 2040s (compared to the period 1915 to 2006) under the same scenario as the left figure (A1B).[29] Streamflow reductions such as these would stress freshwater fish species (for instance, endangered salmon and bull trout) and necessitate increasing tradeoffs among conflicting uses of summer water. Watersheds with significant groundwater contributions to summer streamflow may be less responsive to climate change than indicated here.[26]

Averaged over the region, the number of days with more than one inch of precipitation is projected to increase 13% in 2041 to 2070 compared with 1971 to 2000 under a scenario that assumes a continuation of current rising emissions trends (A2),[10] though these projections are not consistent across models.[28] This increase in heavy downpours could increase flood risk in mixed rain-snow and rain-dominant basins, and could also increase stormwater management challenges in urban areas.

Consequences and Likelihoods of Changes

Reservoir systems have multiple objectives, including irrigation, municipal and industrial use, hydropower production, flood control, and preservation of habitat for aquatic species. Modeling studies indicate, with near 100% likelihood and for all emissions scenarios, that reductions in summer flow will occur by 2050 in basins with significant snowmelt (for example, Elsner et al. 2010[24]). These reduced flows will require more tradeoffs among objectives of the whole system of reservoirs,[30] especially with the added challenges of summer increases in electric power demand for cooling[31] and additional water consumption by crops and forests.[10,32] For example, reductions in hydropower production of as much as 20% by the 2080s could be required to preserve in-stream flow targets for fish in the Columbia River basin.[33] Springtime irrigation diversions increased between 1970 and 2007 in the Snake River basin, as earlier snowmelt led to reduced spring soil moisture.[34] In the absence of human adaptation, annual hydropower production is much more likely to decrease than to increase in the Columbia River basin; economic impacts of hydropower changes could be hundreds of millions of dollars per year.[35]

Region-wide summer temperature increases and, in certain basins, increased river flooding and winter flows and decreased summer flows, will threaten many freshwater species, particularly salmon, steelhead, and trout.[27] Rising temperatures will increase disease and/or mortality in several iconic salmon species, especially for spring/summer Chinook and sockeye in the interior Columbia and Snake River basins.[36] Some Northwest streams[30] and lakes have already warmed over the past three decades, contributing to changes such as earlier Columbia River sockeye salmon migration[37] and earlier blooms of algae in Lake Washington.[38] Relative to the rest of the United States, Northwest streams dominated by snowmelt runoff appear to be less sensitive, in the short term, to warming due to the temperature buffering provided by snowmelt and groundwater contributions to those streams.[39] However, as snowpack declines, the future sensitivity to warming is likely to increase in these areas.[40] By the 2080s, suitable habitat for the four trout species of the interior western U.S. is projected to decline 47% on average, compared to the period 1978-1997.[41] As species respond to climate change in diverse ways, there is potential for ecological mismatches to occur – such as in the timing of the emergence of predators and their prey.[38]

Adaptive Capacity and Implications for Vulnerability

The ability to adapt to climate changes is strengthened by extensive water resources infrastructure, diversity of institutional arrangements,[42] and management agencies that are responsive to scientific input. However, over-allocation of existing water supply, conflicting objectives, limited management flexibility caused by rigid water allocation and operating rules, and other institutional barriers to changing operations continue to limit progress towards adaptation in many parts of the Columbia River basin.[43,44] Vulnerability to projected changes in snowmelt timing is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated, mid-elevation, temperature-sensitive, mixed rain-snow watersheds with existing conflicts among users of summer water. Regional power planners have expressed concerns over the existing hydroelectric system's potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints.[1] Vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins) and where institutional arrangements are simple and current natural and human demands rarely exceed current water availability.[43,45,46]

The adaptive capacity of freshwater ecosystems also varies and, in managed basins, will depend on the degree to which the need to maintain streamflows and water quality for fish and wildlife is balanced with human uses of water resources. In highly managed rivers, release of deeper, colder water from reservoirs could offer one of the few direct strategies to lower water temperatures downstream.[47] Actions to improve stream habitat, including planting trees for shade, are being tested. Some species may be able to change behavior or take advantage of cold-water refuges.[48]

Key Message 2: Coastal Vulnerabilities

In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

With diverse landforms (such as beaches, rocky shorelines, bluffs, and estuaries), coastal and marine ecosystems, and human uses (such as rural communities, dense urban areas, international ports, and transportation), the Northwest coast will experience a wide range of climate impacts.

Description of Observed and Projected Changes

Global sea levels have risen about 8 inches since 1880 and are projected to rise another 1 to 4 feet by 2100 (Ch. 2: Our Changing Climate, Key Message 10). Many local and regional factors can modify the global trend, including vertical land movement, oceanic winds and circulation, sediment compaction, subterranean fluid withdrawal (such as groundwater and natural gas), and other geophysical factors such as the gravitational effects of major ice sheets and glaciers on regional ocean levels.

Much of the Northwest coastline is rising due to a geophysical force known as "tectonic uplift," which raises the land surface. Because of this, apparent sea level rise is less than the currently observed global average. However, a major earthquake along the Cascadia subduction zone, expected within the next few hundred years, would immediately reverse centuries of uplift and, based on historical evidence, increase relative sea level 40 inches or more.[49,50] On the other hand, some Puget Sound locations are currently experiencing subsidence (where land is sinking or settling) and could see the reverse effect, witnessing immediate uplift during a major earthquake and lowered relative sea levels.[51,52]

Taking into account many of these factors and considering a wider range of emissions scenarios than are used in this assessment (Appendix 5: Scenarios and Models), a recent

Projected Relative Sea Level Rise for the Latitude of Newport, Oregon

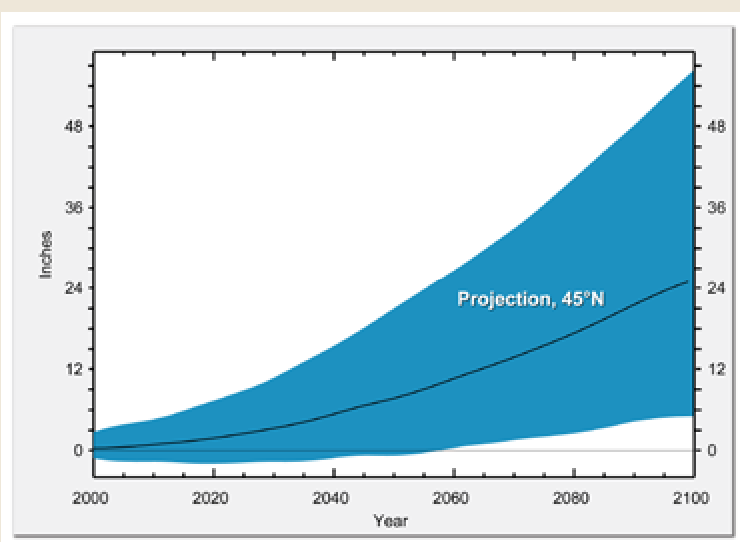

Figure 21.3. Projected relative sea level rise for the latitude of Newport, Oregon (relative to the year 2000) is based on a broader suite of emissions scenarios (ranging from B1 to A1FI) and a more detailed and regionally-focused calculation than those generally used in this assessment (see Ch. 2: Our Changing Climate).[50] The blue area shows the range of relative sea level rise, and the black line shows the projection, which incorporates global and regional effects of warming oceans, melting land ice, and vertical land movements.[50] Given the difficulty of assigning likelihood to any one possible trajectory of sea level rise at this time, a reasonable risk assessment would consider multiple scenarios within the full range of possible outcomes shown, in conjunction with long- and short-term compounding effects, such as El Niño-related variability and storm surge. (Data from NRC 2012[50]).

evaluation calculated projected sea level rise and ranges for the years 2030, 2050, and 2100 (relative to 2000) based on latitude for Washington, Oregon, and California (see Figure 21.3).[50] In addition to long-term climate-driven changes in sea level projected for the Northwest, shorter-term El Niño conditions can increase regional sea level by about 4 to 12 inches for periods of many months.[50,53]

Northwest coastal waters, some of the most productive on the West Coast,[54] have highly variable physical and ecological conditions as a result of seasonal and year-to-year changes in upwelling of deeper marine water that make longer-term changes difficult to detect. Coastal sea surface temperatures have increased[55] and summertime fog has declined between 1900 and the early 2000s, both of which could be consequences of weaker upwelling winds.[56] Projected changes include increasing but highly variable acidity,[57,58,59] increasing surface water temperature (2.2°F from the period 1970 to 1999 to the period 2030 to 2059),[60] and possibly changing storminess.[61] Climate models show inconsistent projections for the future of Northwest coastal upwelling.[12,62]

Consequences and Likelihoods of Changes

In Washington and Oregon, more than 140,000 acres of coastal lands lie within 3.3 feet in elevation of high tide.[63] As sea levels continue to rise, these areas will be inundated more frequently. Many coastal wetlands, tidal flats, and beaches will probably decline in quality and extent as a result of sea level rise, particularly where habitats cannot shift inland because of topographical limitations or physical barriers resulting from human development. Species such as shorebirds and forage fish (small fish eaten by larger fish, birds, or mammals) would be harmed, and coastal infrastructure and communities would be at greater risk from coastal storms.[64]

Ocean acidification threatens culturally and commercially significant marine species directly affected by changes in ocean chemistry (such as oysters) and those affected by changes in the marine food web (such as Pacific salmon[65]). Northwest coastal waters are among the most acidified worldwide, especially in spring and summer with coastal upwelling[58,59,66] combined with local factors in estuaries.[57,58]

Increasing coastal water temperatures and changing ecological conditions may alter the ranges, types, and abundances of marine species.[67,68] Recent warm periods in the coastal ocean, for example, saw the arrival of subtropical and offshore marine species from zooplankton to top predators such as striped marlin, tuna, and yellowtail more common to the Baja area.[69] Warmer water in regional estuaries (such as Puget Sound) may contribute to a higher incidence of harmful blooms of algae linked to paralytic shellfish poisoning,[70] and may result in adverse economic impacts from beach closures affecting recreational harvesting of shellfish such as razor clams.[71] Toxicity of some harmful algae appears to be increased by acidification.[72]

Rising Sea Levels and Changing Flood Risks in Seattle

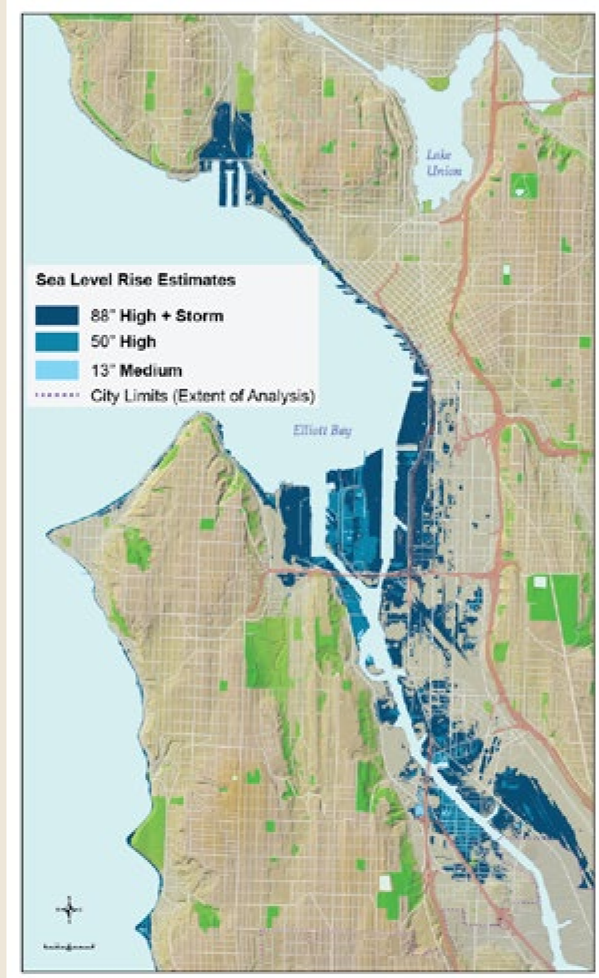

Figure 21.4. Areas of Seattle projected by Seattle Public Utilities to be below sea level during high tide (Mean Higher High Water) and therefore at risk of flooding or inundation are shaded in blue under three levels of sea level rise,[78] assuming no adaptation. (High [50 inches] and medium [13 inches] levels are within the range projected for the Northwest by 2100; the highest level [88 inches] includes the compounding effect of storm surge, derived from the highest observed historical tide in Seattle[79]). Unconnected inland areas shown to be below sea level may not be inundated, but could experience problems due to areas of standing water caused by a rise in the water table and drainage pipes backed up with seawater. (Figure source: Seattle Public Utilities[80]).

Many human uses of the coast – for living, working, and recreating – will also be negatively affected by the physical and ecological consequences of climate change. Erosion, inundation, and flooding will threaten public and private property along the coast; infrastructure, including wastewater treatment plants;[7,73] stormwater outfalls;[74,75] ferry terminals;[76] and coastal road and rail transportation, especially in Puget Sound.[77] Municipalities from Seattle[74] and Olympia,[75] Washington, to Neskowin, Oregon, have mapped risks from the combined effects of sea level rise and other factors.

Adaptive Capacity and Implications for Vulnerability

Human activities have increased the vulnerability of many coastal ecosystems, by degrading and eliminating habitat[81] and by building structures that, along with natural bluffs, thwart inland movement of many remaining habitats. In Puget Sound, for example, seawalls, bulkheads, and other structures have modified an estimated one-third of the shoreline,[82] though some restoration has occurred. Human responses to erosion and sea level rise, especially shoreline armoring, will largely determine the viability of many shallow-water and estuarine ecosystems.[68,82,83] In communities with few alternatives to existing coastal transportation networks, such as on parts of Highway 101 in Oregon, sea level rise and storm surges will pose an increasing threat to local commerce and livelihoods. Finally, there are few proven options for ameliorating projected ocean acidification.[84]

Adapting the Nisqually River Delta to Sea Level Rise

Figure 21.5. In Washington's Nisqually River Delta, estuary restoration on a large scale to assist salmon and wildlife recovery provides an example of adaptation to climate change and sea level rise. After a century of isolation behind dikes (left), much of the Nisqually National Wildlife Refuge was reconnected with tidal flow in 2009 by removal of a major dike and restoration of 762 acres (right), with the assistance of Ducks Unlimited and the Nisqually Indian Tribe. This reconnected more than 21 miles of historical tidal channels and floodplains with Puget Sound.[85] A new exterior dike was constructed to protect freshwater wetland habitat for migratory birds from tidal inundation and future sea level rise. Combined with expansion of the authorized Refuge boundary, ongoing acquisition efforts to expand the Refuge will enhance the ability to provide diverse estuary and freshwater habitats despite rising sea level, increasing river floods, and loss of estuarine habitat elsewhere in Puget Sound. This project is considered a major step in increasing estuary habitat and recovering the greater Puget Sound estuary. (Photo credits: (left) Jesse Barham, U.S. Fish and Wildlife Service; (right) Jean Takekawa, U.S. Fish and Wildlife Service).

Key Message 3: Impacts on Forests

The combined impacts of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.

Evergreen coniferous forests are a prominent feature of Northwest landscapes, particularly in mountainous areas. Forests support diverse fish and wildlife species, promote clean air and water, stabilize soils, and store carbon. They support local economies and traditional tribal uses and provide recreational opportunities.

Description of Observed and Projected Changes

Climate change will alter Northwest forests by increasing wildfire risk and insect and tree disease outbreaks, and by forcing longer-term shifts in forest types and species (see Ch 7: Forests). Many impacts will be driven by water deficits, which increase tree stress and mortality, tree vulnerability to insects, and fuel flammability. The cumulative effects of disturbance – and possibly interactions between insects and fires – will cause the greatest changes in Northwest forests.[86,87] A similar outlook is expected for the Southwest region (see Ch. 20: Southwest, Key Message 3).

Although wildfires are a natural part of most Northwest forest ecosystems, warmer and drier conditions have helped increase the number and extent of wildfires in western U.S. forests since the 1970s.[14,87,88,89] This trend is expected to continue under future climate conditions. By the 2080s, the median annual area burned in the Northwest would quadruple relative to the 1916 to 2007 period to 2 million acres (range of 0.2 to 9.8 million acres) under the A1B scenario. Averaged over the region, this would increase the probability that 2.2 million acres would burn in a year from 5% to nearly 50%.[14] Within the region, this probability will vary substantially with sensitivity of fuels to climatic conditions and local variability in fuel type and amount, which are in turn a product of forest type, effectiveness of fire suppression, and land use. For example, in the Western Cascades, the year-to-year variability in area burned is difficult to attribute to climate conditions, while fire in the eastern Cascades and other specific vegetation zones is responsive to climate.[14] How individual fires behave in the future and what impacts they have will depend on factors we cannot yet project, such as extreme daily weather and forest fuel conditions.

Higher temperatures and drought stress are contributing to outbreaks of mountain pine beetles that are increasing pine mortality in drier Northwest forests.[90,91] This trend is projected to continue with ongoing warming.[14,92,93,94] Between now and the end of this century, the elevation of suitable beetle habitat is projected to increase as temperature increases, exposing higher-elevation forests to the pine beetle, but ultimately limiting available area as temperatures exceed the beetles' optimal temperatures.[14,92,93] As a result, the proportion of Northwest pine forests where mountain pine beetles are most likely to survive is projected to first increase (27% higher in 2001 to 2030 compared to 1961 to 1990) and then decrease (about 49% to 58% lower by 2071 to 2100).[92] For many tree species, the most climatically suited areas will shift from their current locations, increasing vulnerability to insects, disease, and fire in areas that become unsuitable. Eighty-five percent of the current range of three species that are host to pine beetles is projected to be climatically unsuitable for one or more of those species by the 2060s,[14,95] while 21 to 38 currently existing plant species may no longer find climatically appropriate habitat in the Northwest by late this century.[96]

Forest Mortality

Figure 21.6. Forest mortality due to fire and insect activity is already evident in the Northwest. Continued changes in climate in coming decades are expected to increase these effects. Trees killed by a fire (left side of watershed) and trees killed by mountain pine beetle and spruce beetle infestations (orange and gray patches, right side of watershed) in subalpine forest in the Pasayten Wilderness, Okanogan Wenatchee National Forest, Washington, illustrates how cumulative disturbances can affect forests. (Photo credit: Jeremy Littell, USGS).

Consequences and Likelihoods of Changes

The likelihood of increased disturbance (fire, insects, diseases, and other sources of mortality) and altered forest distribution are very high in areas dominated by natural vegetation, and the resultant changes in habitat would affect native species and ecosystems. Subalpine forests and alpine ecosystems are especially at risk and may undergo almost complete conversion to other vegetation types by the 2080s (A2 and B1;[104] A2;[105] Ensemble A2, B1, B2;[106]). While increased area burned can be statistically estimated from climate projections, changes in the risk of very large, high-intensity, stand-replacing fires cannot yet be predicted, but such events could have enormous impacts for forest-dependent species.[88] Increased wildfire could exacerbate respiratory and cardiovascular illnesses in nearby populations due to smoke and particulate pollution (Ch. 9: Human Health).[107,108]

These projected forest changes will have moderate economic impacts for the region as a whole, but could significantly affect local timber revenues and bioenergy markets.[109]

Insects and Fire in Northwest Forests

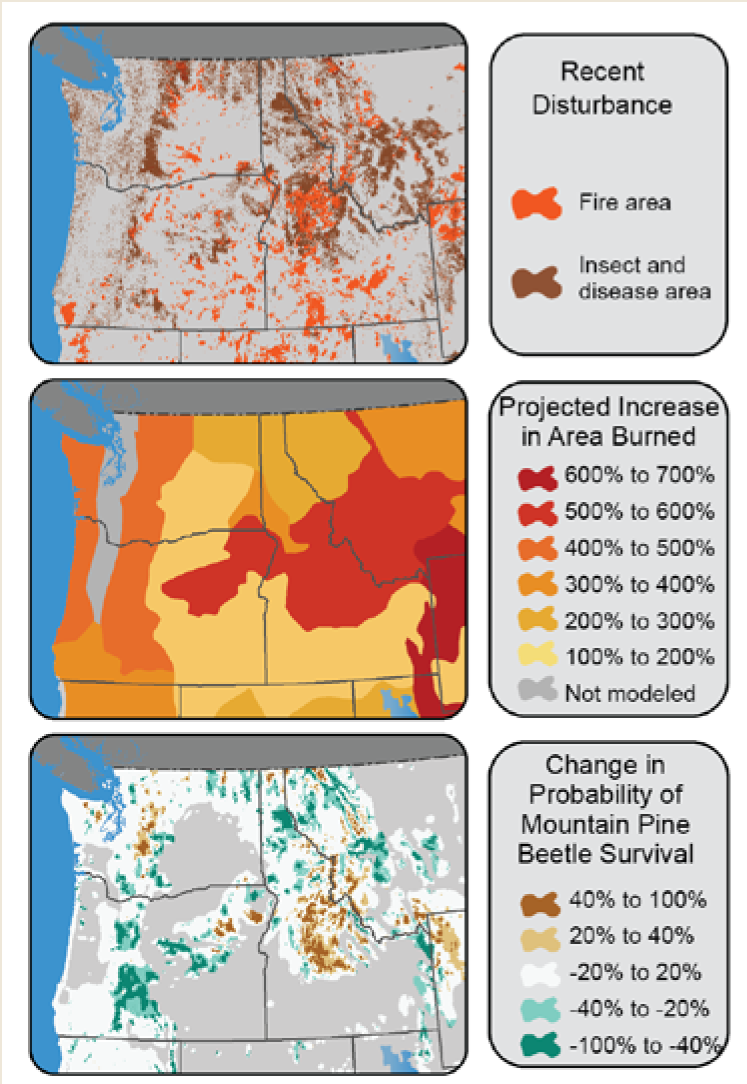

Figure 21.7.

(Top) Insects and fire have cumulatively affected large areas of the Northwest and are projected to be the dominant drivers of forest change in the near future. Map shows areas recently burned (1984 to 2008)[97,98] or affected by insects or disease (1997 to 2008).[99]

(Middle) Map indicates the increases in area burned that would result from the regional temperature and precipitation changes associated with a 2.2°F global warming[100] across areas that share broad climatic and vegetation characteristics.[101] Local impacts will vary greatly within these broad areas with sensitivity of fuels to climate.[14]

(Bottom) Projected changes in the probability of climatic suitability for mountain pine beetles for the period 2001 to 2030 (relative to 1961 to 1990), where brown indicates areas where pine beetles are projected to increase in the future and green indicates areas where pine beetles are expected to decrease in the future. Changes in probability of survival are based on climate-dependent factors important in beetle population success, including cold tolerance,[102] spring precipitation,[103] and seasonal heat accumulation.[91,92]

Adaptive Capacity and Implications for Vulnerability

Ability to prepare for these changes varies with land ownership and management priorities. Adaptation actions that decrease forest vulnerability exist, but none is appropriate across all of the Northwest's diverse climate threats, land-use histories, and management objectives.[86,110] Surface and canopy thinning can reduce the occurrence and effects of high severity fire in currently low severity fire systems, like drier eastern Cascades forests,[111] but may be ineffective in historically high-severity-fire forests, like the western Cascades, Olympics, and some subalpine forests. It is possible to use thinning to reduce tree mortality from insect outbreaks,[86,112] but not on the scale of the current outbreaks in much of the West.

Key Message 4: Adapting Agriculture

While the agriculture sector's technical ability to adapt to changing conditions can offset some adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Agriculture provides the economic and cultural foundation for Northwest rural populations and contributes substantively to the overall economy. Agricultural commodities and food production systems contributed 3% and 11% of the region's gross domestic product, respectively, in 2009.[113] Although the overall consequences of climate change will probably be lower in the Northwest than in certain other regions, sustainability of some Northwest agricultural sectors is threatened by soil erosion[114] and water supply uncertainty, both of which could be exacerbated by climate change.

Description of Observed and Projected Changes

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, a specific range of temperatures, precipitation, and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming will reduce the availability of irrigation water in snowmelt-fed basins and increase the probability of heat stress to field crops and tree fruit. Some crops will benefit from a longer growing season[115] and/or higher atmospheric carbon dioxide, at least for a few decades.[115,116] Longer-term consequences are less certain. Changes in plant diseases, pests, and weeds present additional potential risks. Higher average temperatures generally can exacerbate pest pressure through expanded geographic ranges, earlier emergence or arrival, and increased numbers of pest generations (for example, Ch. 6: Agriculture).[117] Specifics differ among pathogen and pest species and depend upon multiple interactions (Ch. 6: Agriculture)[118] preventing region-wide generalizations. Research is needed to project changes in vulnerabilities to pest, disease, and weed complexes for specific cropping systems in the Northwest.

Consequences of Changes

Because much of the Northwest has low annual precipitation, many crops require irrigation. Reduction in summer flows in snow-fed rivers (see Figure 21.2), coupled with warming that could increase agricultural and other demands, potentially produces irrigation water shortages.[108] The risk of a water-short year – when Yakima basin junior water rights holders are allowed only 75% of their water right amount – is projected to increase from 14% in the late 20th century to 32% by 2020 and 77% by 2080, assuming no adaptation and under the A1B scenario.[46]

Assuming adequate nutrients and excluding effects of pests, weeds, and diseases, projected increases in average temperature and hot weather episodes and decreases in summer soil moisture would reduce yields of spring and winter wheat in rain-fed production zones of Washington State by the end of this century by as much as 25% relative to 1975 to 2005. However, carbon dioxide fertilization should offset these effects, producing net yield increases as great as 33% by 2080.[115] Similarly, for irrigated potatoes in Washington State, carbon dioxide fertilization is projected to mostly offset direct climate change related yield losses, although yields are still projected to decline by 2% to 3% under the A1B emissions scenario.[115] Higher temperatures could also reduce potato tuber quality.[119]

Irrigated apple production is projected to increase in Washington State by 6% in the 2020s, 9% in the 2040s, and 16% in the 2080s (relative to 1975 to 2005) when offsetting effects of carbon dioxide fertilization are included.[115] However, because tree fruit requires chilling to ensure uniform flowering and fruit set and wine grape varieties have specific chilling requirements for maturation,[120] warming could adversely affect currently grown varieties of these commodities. Most published projections of climate change impacts on Northwest agriculture are limited to Washington State and have focused on major commodities, although more than 300 crops are grown in the region. More studies are needed to identify the implications of climate change for additional cropping systems and locations within the region. The economic consequences for Northwest agriculture will be influenced by input and output prices driven by global economic conditions as well as by regional and local changes in productivity.

Adaptive Capacity and Implications for Vulnerability

Of the four areas of concern discussed here, agriculture is perhaps best positioned to adapt to climate trends without explicit planning and policy, because it already responds to annual climate variations and exploits a wide range of existing climates across the landscape.[121] Some projected changes in climate, including warmer winters, longer annual frost-free periods, and relatively unchanged or increased winter precipitation, could be beneficial to some agriculture systems. Nonetheless, rapid climate change could present difficulties. Adaptation could occur slowly if substantial investments or significant changes in farm operations and equipment are required. Shifts to new varieties of wine grapes and tree fruit, if indicated, and even if ultimately more profitable, are necessarily slow and expensive. Breeding for drought- and heat-resistance requires long-term effort. Irrigation water shortages that necessitate shifts away from more profitable commodities could exact economic penalties.[108]

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

The authors and several dozen collaborators undertook a risk evaluation of the impacts of climate change in the Northwest that informed the development of the four key messages in this chapter (see also Ch. 26: Decision Support). This process considered the combination of impact likelihood and the consequences for the region's economy, infrastructure, natural systems, human health, and the economically-important and climate sensitive regional agriculture sector (see Dalton et al. 2013[6] for details). The qualitative comparative risk assessment underlying the key messages in the Northwest chapter was informed by the Northwest Regional Climate Risk Framing workshop (December 2, 2011, in Portland, OR). The workshop brought together stakeholders and scientists from a cross-section of sectors and jurisdictions within the region to discuss and rank the likelihood and consequences for key climate risks facing the Northwest region and previously identified in the Oregon Climate Change Adaptation Framework.[122] The approach consisted of an initial qualitative likelihood assessment based on expert judgment and consequence ratings based on the conclusions of a group of experts and assessed for four categories: human health, economy, infrastructure, and natural systems.[123]

This initial risk exercise was continued by the lead author team of the Northwest chapter, resulting in several white papers that were 1) condensed and synthesized into the Northwest chapter, and 2) expanded into a book-length report on Northwest impacts.[6] The NCA Northwest chapter author team engaged in multiple technical discussions via regular teleconferences and two all-day meetings. These included careful review of the foundational technical input report[123] and approximately 80 additional technical inputs provided to the NCA by the public, as well additional published literature. They also drew heavily from two state climate assessment reports.[124]

The author team identified potential regional impacts by 1) working forward from drivers of regional climate impacts (for example, changes in temperature, precipitation, sea level, ocean chemistry, and storms), and 2) working backward from affected regional sectors (for example, agriculture, natural systems, and energy). The team identified and ranked the relative consequences of each impact for the region's economy, infrastructure, natural systems, and the health of Northwest residents. The likelihood of each impact was also qualitatively ranked, allowing identification of the impacts posing the highest risk, that is, likelihood × consequence, to the region as a whole. The key regionally consequential risks thus identified are those deriving from projected changes in streamflow timing (in particular, warming-related impacts in watersheds where snowmelt is an important contributor to flow); coastal consequences of the combined impact of sea level rise and other climate-related drivers; and changes in Northwest forest ecosystems. The Northwest chapter therefore focuses on the implications of these risks for Northwest water resources, key aquatic species, coastal systems, and forest ecosystems, as well as climate impacts on the regionally important, climate-sensitive agricultural sector.

Each author produced a white paper synthesizing the findings in his/her sectoral area, and a number of key messages pertaining to climate impacts in that area. These syntheses were followed by expert deliberation of draft key messages by the authors wherein each key message was defended before the entire author team before this key message was selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities," including likelihood of climate change and relative magnitude of its consequences for the region as a whole, including consequences for the region's economy, human health, ecosystems, and infrastructure.[123]

Though the risks evaluated were aggregated over the whole region, it was recognized that impacts, risks, and appropriate adaptive responses vary significantly in local settings. For all sectors, the focus on risks of importance to the region's overall economy, ecology, built environment, and health is complemented, where space allows, by discussion of the local specificity of climate impacts, vulnerabilities and adaptive responses that results from the heterogeneity of Northwest physical conditions, ecosystems, human institutions and patterns of resource use.

Key message #1 Traceable Account

Changes in the timing of streamflow related to changing snowmelt are already observed and will continue, reducing the supply of water for many

competing demands and causing far-reaching ecological and socioeconomic consequences.

Description of evidence base

This message was selected because of the centrality of the water cycle to many important human and natural systems of the Northwest: hydropower production and the users of this relatively inexpensive electricity; agriculture and the communities and economies dependent thereon, and; coldwater fish, including several species of threatened and endangered salmon, the tribal and fishing communities and ecosystems that depend on them, and the adjustments in human activities and efforts necessary to restore and protect them. Impacts of water-cycle changes on these systems, and any societal adjustments to them, will have far-reaching ecological and socioeconomic consequences.

Evidence that winter snow accumulation will decline under projected climate change is based on 20^{th} century observations and theoretical studies of the sensitivity of Northwest snowpack to changes in precipitation and temperature. There is good agreement on the physical role of climate in snowpack development, and projections of the sign of future trends are consistent (many studies). However, climate variability creates disagreement over the magnitude of current and near-term future trends.

Evidence that projected climate change would shift the timing and amount of streamflow deriving from snowmelt is based on 20^{th} century observations of climate and streamflow and is also based on hydrologic model simulation of streamflow responses to climate variability and change. There is good agreement on the sign of trends (many studies), though the magnitude of current and near-term future trends is less certain because of climate variability.

Evidence that declining snowpack and changes in the timing of snowmelt-driven streamflow will reduce water supply for many competing and time-sensitive demands is based on:

- hydrologic simulations, driven by future climate projections, that consistently show reductions in spring and summer flows in mixed rain-snow and some snow-dominant watersheds;
- documented competition among existing water uses (irrigation, power, municipal, and in-stream flows) and inability for all water systems to meet all summer water needs all of the time, especially during drier years;
- empirical and theoretical studies that indicate increased water demand for many uses under climate change; and
- policy and institutional analyses of the complex legal and institutional arrangements governing Northwest water management and the challenges associated with adjusting water management in response to changing conditions.

Evidence for far-reaching ecological and socioeconomic consequences of the above is based on:

- model simulations showing negative impacts of projected climate and altered streamflow on many water resource uses at scales ranging from individual basins (for example, Skagit, Yakima) to the region (for example, Columbia River basin);
- model simulations of future agricultural water allocation in the Yakima[46] and the Snake River Basin,[32] showing increased likelihood of water curtailments for junior water rights holders;
- model and empirical studies documenting sensitivity of coldwater fish to water temperatures, sensitivity of water temperature to air temperature, and projected warming of summer stream temperatures;
- regional and extra-regional dependence on Northwest-produced hydropower; and
- legal requirements to manage water resources for threatened & endangered fish as well as for human uses.

Evidence that water users in managed mixed rain-snow basins are likely to be the most vulnerable to climate change and less vulnerable in rain-dominated basins is based on:

- observed, theoretical, and simulated sensitivity of watershed hydrologic response to warming by basin type;
- historical observations and modeled simulations of tradeoffs required among water management objectives under specific climatic conditions;
- analyses from water management agencies of potential system impacts and adaptive responses to projected future climate; and
- institutional and policy analyses documenting sources and types of management rigidity (for example, difficulty adjusting management practices to account for changing conditions).

New information and remaining uncertainties

A key uncertainty is the degree to which current and future interannual and interdecadal variations in climate will enhance or obscure long-term anthropogenic climate trends.

Uncertainty over local groundwater or glacial inputs and other local effects may cause overestimates of increased stream temperature based solely on air temperature. However, including projected decreases in summer streamflow would increase estimates of summer stream temperature increases above those based solely on air temperature.

Uncertainty in how much increasing temperatures will affect crop evapotranspiration affects future estimates of irrigation demand.

Uncertainty in future population growth and changing per capita water use affects estimates of future municipal demand and therefore assessments of future reliability of water resource systems.

A major uncertainty is the degree to which water resources management operations of regulated systems can be adjusted to account for climate-driven changes in the amount and timing of streamflow, and how competing resource objectives will be accommodated or prioritized. Based on current institutional inertia, significant changes are unlikely to occur for several decades.

There is uncertainty in economic assessment of the impacts of hydrologic changes on the Northwest because much of the needed modeling and analysis is incomplete. Economic impacts assessment would require quantifying both potential behavioral responses to future climate-affected economic variables (prices of inputs and products) and to climate change itself. Some studies have sidestepped the issue of behavioral response to these and projected economic impacts based on future scenarios that do not consider adaptation, which lead to high estimates of "costs" or impacts.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Confidence is **very high** based on strong strength of evidence and **high** level of agreement among experts.

See specifics under "description of evidence" above.

Key message #2 Traceable Account

In the coastal zone, the effects of sea level rise, erosion, inundation, threats to infrastructure and habitat, and increasing ocean acidity collectively pose a major threat to the region.

Description of evidence base

Given the extent of the coastline, the importance of coastal systems to the region's ecology, economy, and identity, and the difficulty of adapting in response, the consequences of sea level rise, ocean acidification, and other climate driven changes in ocean conditions and coastal weather are expected to be significant and largely negative, which is why this message was included.

Evidence for observed global (eustatic) sea level rise and regional sea level change derives from satellite altimetry and coastal tide gauges. Evidence for projected global sea level rise is described in Ch. 2: Our Changing Climate, in the recent NRC report[50] that includes a detailed discussion of the U.S. West Coast, and Parris et al. 2012.[125]

Evidence of erosion associated with coastal storms is based on observations of storm damage in some areas of the Northwest.

Evidence for erosion and inundation associated with projected sea level rise is based on observations and mapping of coastal elevations and geospatial analyses of the extent and location of inundation associated with various sea level rise and storm surge scenarios.

Evidence for climate change impacts on coastal infrastructure derives from geospatial analyses (mapping infrastructure locations likely to be affected by various sea level rise scenarios, storm surge scenarios and/or river flooding scenario), such as those undertaken by various local governments to assess local risks of flooding for the downtown area (Olympia), of sea level rise and storm surge for marine shoreline inundation and risk to public utility infrastructure (Seattle – highest observed tide from NOAA tide gauge added to projected sea levels), and of sea level rise for wastewater treatment plants and associated infrastructure (King County). Vulnerability of coastal transportation infrastructure to climate change has been assessed by combining geospatial risk analyses with expert judgment of asset sensitivity to climate risk and criticality to the transportation system in Washington State and by assessing transportation infrastructure exposure to climate risks associated with sea level rise and river flooding in the region as a whole.

Evidence for impacts of climate change on coastal habitat is based on:

- model-based studies of projected impacts of sea level rise on tidal habitat showing significant changes in the composition and extent of coastal wetland habitats in Washington and Oregon;
- observations of extent and location of coastal armoring and other structures that would potentially impede inland movement of coastal wetlands;
- observed changes in coastal ocean conditions (upwelling, nutrients, and sea surface temperatures); biogeographical, physiological, and paleoecological studies indicating a historical decline in coastal upwelling; and global climate model projections of future increases in sea surface temperatures;
- modeled projections for increased risk of harmful algal blooms (HABs) in Puget Sound associated with higher air and water temperatures, reduced streamflow, low winds, and small tidal variability (i.e., these conditions offer a favorable window of opportunity for HABs); and
- observed changes in the geographic ranges, migration timing, and productivity of marine species due to changes in sea surface temperatures associated with cyclical events, such as the interannual El Niño Southern Oscillation and the inter-decadal Pacific Decadal Oscillation and North Pacific Gyre Oscillation.

Evidence for historical increases in ocean acidification is from observations of changes in coastal ocean conditions, which also indicate high spatial and temporal variability. Evidence for acidification's effects on various species and the broader marine food web is still emerging but is based on observed changes in abundance, size, and mortality of marine calcifying organisms and laboratory based and in situ acidification experiments.

Evidence for marine species responses to climate change derives from observations of shifts in marine plankton, fish, and seabird species associated with historical changes in ocean conditions, including temperature and availability of preferred foods.

Evidence for low adaptive capacity is from observations of extent of degraded or fragmented coastal habitat, existence of few options for mitigating changes in marine chemical properties, observed extent of barriers to inland habitat migration, narrow coastal transportation corridors, and limited transportation alternatives for rural coastal towns. Evidence for low adaptive capacity is also based on the current limitations (both legal and political) of local and state governments to restrict and/or influence shoreline modifications on private lands.

New information and remaining uncertainties

There is significant but well-characterized uncertainty about the rate and extent of future sea level rise at both the global and regional/sub-regional scales. However, there is virtually no uncertainty in the direction (sign) of global sea level rise. There is also a solid understanding of the primary contributing factors and mechanisms causing sea level rise. Other details concerning uncertainty in global sea level rise are treated elsewhere (for example, NRC 2012[50]) and in Ch. 2: Our Changing Climate). Regional uncertainty in projected Northwest sea level rise results primarily from global factors such as ice sheet mass balance and local vertical land movement (affecting relative sea level rise). An accurate determination of vertical land deformation requires a sufficient density of monitoring sites (for example, NOAA tide gauges and permanent GPS sites that monitor deformation) to capture variations in land deformation over short spatial scales, and in many Northwest coastal locations such dense networks do not exist. There is a general trend, however, of observed uplift along the northwestern portion of the Olympic Peninsula and of subsidence within the Puget Sound region (GPS data gathered from PBO data sets -- http://pbo.unavco.org/data/gps; see also Chapman and Melbourne 2009[51]).

There is also considerable uncertainty about potential impacts of climate change on processes that influence storminess and affect coastal erosion in the Northwest. These uncertainties relate to system complexity and the limited number of studies and lack of consensus on future atmospheric and oceanic conditions that will drive changes in regional wind fields. Continued collection and assessment of meteorological data at ocean buoy locations and via remote sensing should improve our understanding of these processes.

Uncertainty in future patterns of sediment delivery to the coastal system limit projections of future inundation, erosion, and changes in tidal marsh. For example, substantial increases in riverine sediment delivery, due to climate-related changes in the amount and timing of streamflow, could offset erosion and/or inundation projected from changes in sea level alone. However, there are areas in the Northwest where it is clear that man-made structures have interrupted sediment supply and there is little uncertainty that shallow water habitat will be lost.

Although relatively well-bounded, uncertainty over the rate of projected relative sea level rise limits our ability to assess whether any particular coastal habitat will be able to keep pace with future changes through adaptation (for example, through accretion).

The specific implications of the combined factors of sea level rise, coastal climate change, and ocean acidification for coastal ecosystems and specific individual species remain uncertain due to the complexity of ecosystem response. However, there is general agreement throughout the peer-reviewed literature that negative impacts for a number of marine calcifying organisms are projected, particularly during juvenile life stages.

Projections of future coastal ocean conditions (for example, temperature, nutrients, pH, and productivity) are limited, in part, by uncertainty over future changes in upwelling – climate model scenarios show inconsistent projections for likely future upwelling conditions. Considerable uncertainty also remains in whether, and how, higher average ocean temperatures will influence geographical ranges, abundances, and diversity of marine species, although evidence of changes in pelagic fish species ranges and in production associated with Pacific Ocean temperature variability during cyclical events have been important indicators for potential species responses to climate change in the future. Consequences from ocean acidification for commercial fisheries and marine food web dynamics are potentially very high – while the trend of increasing acidification is very likely, the rate of change and spatial variability within coastal waters are largely unknown and are the subject of ongoing and numerous nascent research efforts.

Additional uncertainty surrounds non-climate contributors to coastal ocean chemistry (for example, riverine inputs, anthropogenic carbon, and nitrogen point and non-point source inputs) and society's ability to mitigate these inputs.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

There is **very high** confidence in the global upward trend of sea level rise (SLR) and ocean acidification (OA). There is **high** confidence that SLR over the next century will remain under an upper bound of approximately 2 meters. Projections for SLR and OA at specific locations are much less certain (**medium to low**) because of the high spatial variability and multiple factors influencing both phenomena at regional and sub-regional scales.

There is **medium** confidence in the projections of species response to sea level rise and increased temperatures, but **low** confidence in species response to ocean acidification. Uncertainty in upwelling changes result in **low** confidence for projections of future change that depend on specific coastal ocean temperatures, nutrient contents, dissolved oxygen content, stratification, and other factors.

There is **high** confidence that significant changes in the type and distribution of coastal marsh habitat are likely, but **low** confidence in our current ability to project the specific location and timing of changes.

There is **high** confidence in the projections of increased erosion and inundation.

There is **very high** confidence that ocean acidity will continue to increase.

Key message #3 Traceable Account

The combined impact of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are virtually certain to cause additional forest mortality by the 2040s and long-term transformation of forest landscapes. Under higher emissions scenarios, extensive conversion of subalpine forests to other forest types is projected by the 2080s.

Description of evidence base

Evidence that the area burned by fire has been high, relative to earlier in the century, since at least the 1980s is strong. Peer-reviewed papers based on federal fire databases (for example, National Interagency Fire Management Integrated Database [NIFMID], 1970/1980-2011) and independent satellite data (Monitoring Trends in Burn Severity [MTBS], 1984-2011) indicate increases in area burned.[98,126]

Evidence that the interannual variation in area burned was at least partially controlled by climate during the period 1980-2010 is also strong. Statistical analysis has shown that increased temperature (related to increased potential evapotranspiration, relative humidity, and longer fire seasons) and decreased precipitation (related to decreased actual evapotranspiration, decreased spring snowpack, and longer fire seasons) are moderate to strong (depending on forest type) correlates to the area and number of fires in the Pacific Northwest. Projections of area burned with climate change are documented in peer-reviewed literature, and different approaches (statistical modeling and dynamic global vegetation modeling) agree on the order of magnitude of those changes for Pacific Northwest forests, though the degree of increase depends on the climate change scenario and modeling approach.

Evidence from aerial disease and detection surveys jointly coordinated by the U.S. Forest Service and state level governments supports the statement that the area of forest mortality caused by insect outbreaks (including the mountain pine beetle) and by tree diseases is increasing.

Evidence that mountain pine beetle and spruce bark beetle outbreaks are climatically controlled is from a combination of laboratory experiments and mathematical modeling reported in peer-reviewed literature. Peer-reviewed future projections of climate have been used to develop projections of mountain pine beetle and spruce beetle habitat suitability based on these models, and show increases in the area of climatically suitable habitat (particularly at mid- to high elevations) by the mid-21st century, but subsequent (late 21st century) declines in suitable habitat, particularly at low- to mid-elevation. There is considerable spatial variability in the patterns of climatically suitable habitat.

Evidence for long-term changes in the distribution of vegetation types and tree species comes from statistical species models, dynamic vegetation models, and other approaches and uses the correlation between observed climate and observed vegetation distributions to model future climatic suitability. These models agree broadly in their conclusions that future climates will be unsuitable for historically present species over significant areas of their ranges and that broader vegetation types will likely change, but the details depend greatly on climate change scenario, location within the region, and forest type.

Evidence that subalpine forests are likely to undergo almost complete conversion to other vegetation types is moderately strong (relatively few studies, but good agreement) and comes from dynamic global vegetation models that include climate, statistical models that relate climate and biome distribution, and individual statistical species distribution models based on climatic variables. The fact that these three different approaches generally agree about the large decrease in area of subalpine forests despite different assumptions, degrees of "mechanistic" simulation, and levels of ecological hierarchy justifies the key message.

New information and remaining uncertainties

The key uncertainties are primarily the timing and magnitude of future projected changes in forests, rather than the direction (sign) of changes.

The rate of expected change is affected by the rate of climate change – higher emissions scenarios have higher impacts earlier in studies that consider multiple scenarios. Most impacts analyses reported in the literature and synthesized here use emissions scenario A1B or A2. Projections of changes in the proportion of Northwest pine forests where mountain pine beetles are likeliest to survive and of potential conversion of subalpine forests used scenario A2.

Statistical fire models do not include changes in vegetation that occur in the 21st century due to disturbance (such as fire, insects, and tree diseases) and other factors such as land-use change and fire suppression changes. As conditions depart from the period used for model training, projections of future fire become more uncertain, and by the latter 21st century (beyond about the 2060s to 2080s), statistical models may over-predict area burned. Despite this uncertainty, the projections from statistical models are broadly similar to those from dynamic global vegetation models (DGVMs), which explicitly simulate changes in future vegetation. A key difference is for forest ecosystems where fire has been rare since the mid 20th century, such as the Olympic Mountains and Oregon coast range, and statistical models are comparatively weak. In these systems, statistical fire models likely underestimate the future area burned, whereas DGVMs may capably simulate future events that are outside the range of the statistical model's capability. In any case, an increase in forest area burned is nearly ubiquitous in these studies regardless of method, but the amount of increase and the degree to which it varies with forest type is less certain. However, fire risk in any particular location or at any particular time is beyond the capability of current model projections. In addition, the statistical model approaches to future fire cannot address fundamental changes in fire behavior due to novel extreme weather patterns, so conclusions about changes in fire severity are not necessarily warranted.

Only a few insects have had sufficient study to understand their climatic linkages, and future insect outbreak damage from other insects, currently unstudied, could increase the estimate of future areas of forest mortality due to insects.

Fire-insect interactions and diseases are poorly studied – the actual effects on future landscapes could be greater if diseases and interactions were considered more explicitly.

For subalpine forests, what those forests become instead of subalpine forests is highly uncertain – different climate models used to drive the same dynamic global vegetation model agree about loss of subalpine forests, but disagree about what will replace them. In addition, statistical approaches that consider biome level and species level responses without the ecological process detail of DGVMs show similar losses, but do not agree on responses, which depend on climate scenarios. Because these statistical models simulate neither the regeneration of seedlings nor the role of disturbances, the future state of the system is merely correlative and based on the statistical relationship between climate and historical forest distribution.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

The observed effects of climate on fires and insects combined with the agreement of future projections across modeling efforts warrants **very high** confidence that increased disturbance will increase forest mortality due to area burned by fire, and increases in insect outbreaks also have **very high** confidence until at least the 2040s in the Northwest. The timing and nature of the rates and the sources of mortality may change, but current estimates may be conservative for insect outbreaks due to the unstudied impacts of other insects. But in any case, the rate of projected forest disturbance suggests that changes will be driven by disturbance more than by gradual changes in forest cover or species composition. After mid-21st century, uncertainty about the interactions between disturbances and landscape response limits confidence to **high** because total area disturbed could begin to decline as most of the landscape becomes outside the range of historical conditions. The fact that different modeling approaches using a wide variety of climate scenarios indicate similar losses of subalpine forests justifies **high** confidence; however, comparatively little research that simulates ecological processes of both disturbance and regeneration as a function of climate, so there is **low** confidence on what will replace them.

Key message #4 Traceable Account

While agriculture's technical ability to adapt to changing conditions can offset some of the adverse impacts of a changing climate, there remain critical concerns for agriculture with respect to costs of adaptation, development of more climate resilient technologies and management, and availability and timing of water.

Description of evidence base

Northwest agriculture's sensitivity to climate change stems from its dependence on irrigation water, adequate temperatures, precipitation and growing seasons, and the sensitivity of crops to temperature extremes. Projected warming trends based on global climate models and emissions scenarios potentially increase temperature-related stress on annual and perennial crops in the summer months.

Evidence for projected impacts of warming on crop yields consists primarily of published studies using crop models indicating increasing vulnerability with projected warming over 1975-2005 baselines. These models also project that thermal-stress-related losses in agricultural productivity will be offset or overcompensated by fertilization from accompanying increases in atmospheric CO_2. These models have been developed for key commodities including wheat, apples, and potatoes. Longer term, to end of century, models project crop losses from temperature stress to exceed the benefits of CO_2 fertilization.

Evidence for the effects of warming on suitability of parts of the region for specific wine grape and tree fruit varieties are based on well-established and published climatic requirements for these varieties.

Evidence for negative impacts of increased variability of precipitation on livestock productivity due to stress on range and pasture consists of a few economic studies in states near the region; relevance to Northwest needs to be established.

Evidence for negative impacts of warming on dairy production in the region is based on a published study examining projected summer heat-stress on milk production.

Evidence for reduction in available irrigation water is based on peer-reviewed publications and state and federal agency reports utilizing hydrological models and precipitation and snowpack projections. These are outlined in more detail in the traceable account for Key Message 1 of this chapter. Increased demands for irrigation water with warming are based on cropping systems models and projected increases in acres cultivated. These projections, coupled with those for water supply, indicate that some areas will experience increased water shortages. Water rights records allow predictions of the users most vulnerable to the effects of these shortages.

Projections for surface water flows include decreases in summer flow related to changes in snowpack dynamics and reductions in summer precipitation. Although these precipitation projections are less certain than those concerning temperatures, they indicate that water shortages for irrigation will be more frequent in some parts of the region, based especially on a Washington State Department of Ecology-sponsored report that considered the Columbia basin. Other evidence for these projected changes in water is itemized in Key Message 1 of this chapter.

Evidence that agriculture has a high potential for autonomous adaptation to climate change, assuming adequate water availability, is inferred primarily from the wide range of production practices currently being used across the varied climates of the region.

New information and remaining uncertainties

Although increasing temperatures can affect the distribution of certain pest, weed, and pathogen species, existing models are limited. Without more comprehensive studies, it is not possible to project changes in overall pressure from these organisms, so overall effects remain uncertain. Some species may be adversely affected by warming directly or through enhancement of their natural enemy base, while others become more serious threats.

Uncertainty exists in models in how increasing temperatures will impact crop evapotranspiration, which affects future estimates of irrigation demand (Key Message 1 of this chapter).

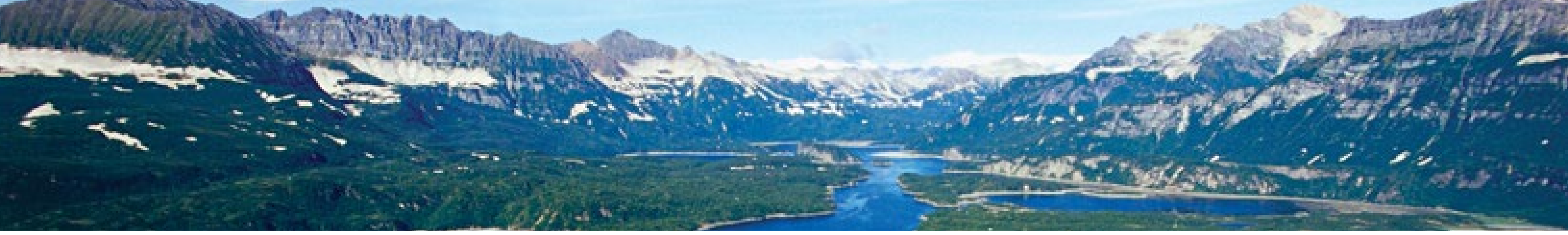
Shifting international market forces including commodity prices and input costs, adoption of new crops, which may have different heat tolerance or water requirements, and technological advances are difficult or impossible to project, but may have substantial effects on agriculture's capacity to adapt to climate change.

Estimates of changes in crop yields as a result of changing climate and CO_2 are based on very few model simulations, so the uncertainty has not been well quantified.

Assessment of confidence based on evidence and agreement or, if defensible, estimates of the likelihood of impact or consequence

Confidence is **very high** based on strong strength of evidence and high level of agreement among experts.

See specifics under "description of evidence" above.



Climate Change Impacts in the United States

CHAPTER 22
ALASKA

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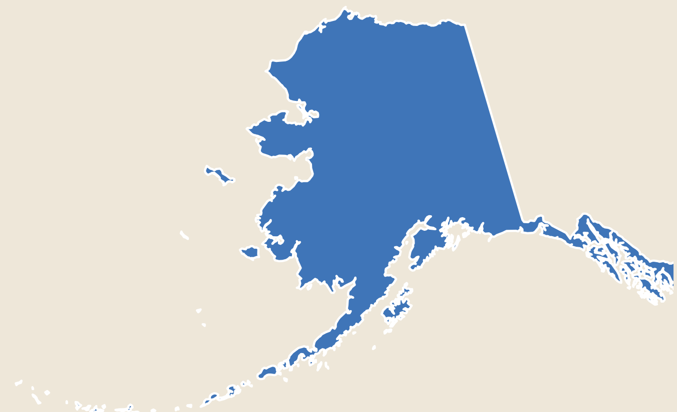

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22 ALASKA

Key Messages

1. **Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.**
2. **Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.**
3. **Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.**
4. **Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.**
5. **The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.**

Alaska is the United States' only Arctic region. Its marine, tundra, boreal (northern) forest, and rainforest ecosystems differ from most of those in other states and are relatively intact. Alaska is home to millions of migratory birds, hundreds of thousands of caribou, some of the world's largest salmon runs, a significant proportion of the nation's marine mammals, and half of the nation's fish catch.[1]

Energy production is the main driver of the state's economy, providing more than 80% of state government revenue and thousands of jobs.[2] Continuing pressure for oil, gas, and mineral development on land and offshore in ice-covered waters increases the demand for infrastructure, placing additional stresses on ecosystems. Land-based energy exploration will be affected by a shorter season when ice roads are viable, yet reduced sea ice extent may create more opportunity for offshore development. Climate also affects hydropower generation.[3] Mining and fishing are the second and third largest industries in the state, with tourism rapidly increasing since the 1990s.[2] Fisheries are vulnerable to changes in fish abundance and dis-

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tribution that result from both climate change and fishing pressure. Tourism might respond positively to warmer springs and autumns[4] but negatively to less favorable conditions for winter activities and increased summer smoke from wildfire.[5]

Alaska is home to 40% (229 of 566) of the federally recognized tribes in the United States.[6] The small number of jobs, high cost of living, and rapid social change make rural, predominantly Native, communities highly vulnerable to climate change through impacts on traditional hunting and fishing and cultural connection to the land and sea. Because most of these communities are not connected to the state's road system or electrical grid, the cost of living is high, and it is challenging to supply food, fuel, materials, health care, and other services. Climate impacts on these communities are magnified by additional social and economic stresses. However, Alaskan Native communities have for centuries dealt with scarcity and high environmental variability and thus have deep cultural reservoirs of flexibility and adaptability.

Observed Climate Change

Over the past 60 years, Alaska has warmed more than twice as rapidly as the rest of the United States, with state-wide average annual air temperature increasing by 3°F and average winter temperature by 6°F, with substantial year-to-year and regional variability.[7] Most of the warming occurred around 1976 during a shift in a long-lived climate pattern (the Pacific Decadal Oscillation [PDO]) from a cooler pattern to a warmer one. The PDO has been shown to alternate over time between warm and cool phases. The underlying long-term warming trend has moderated the effects of the more recent shift of the PDO to its cooler phase in the early 2000s.[8] The overall warming has involved more extremely hot days and fewer extremely cold days (Ch. 2: Our Changing Climate, Key Message 7).[7,9]

Because of its cold-adapted features and rapid warming, climate change impacts on Alaska are already pronounced, including earlier spring snowmelt, reduced sea ice, widespread glacier retreat, warmer permafrost, drier landscapes, and more extensive insect outbreaks and wildfire, as described below.

Projected Climate Change

Average annual temperatures in Alaska are projected to rise by an additional 2°F to 4°F by 2050. If global emissions continue to increase during this century, temperatures can be expected to rise 10°F to 12°F in the north, 8°F to 10°F in the interior, and 6°F to 8°F in the rest of the state. Even with substantial emissions reductions, Alaska is projected to warm by 6°F to 8°F in the north and 4°F to 6°F in the rest of the state by the end of the century (Ch. 2: Our Changing Climate, Key Message 3).[7,10]

Annual precipitation is projected to increase, especially in northwestern Alaska,[7] as part of the broad pattern of increases projected for high northern latitudes. Annual precipitation increases of about 15% to 30% are projected for the region by late this century if global emissions continue to increase (A2). All models project increases in all four seasons.[7] However, increases in evaporation due to higher air temperatures and longer growing seasons are expected to reduce water availability in most of the state.[11]

The length of the growing season in interior Alaska has increased 45% over the last century[12] and that trend is projected to continue.[13] This could improve conditions for agriculture where moisture is adequate, but will reduce water storage and increase the risks of more extensive wildfire and insect outbreaks across much of Alaska.[14,15]

Alaska Will Continue to Warm Rapidly

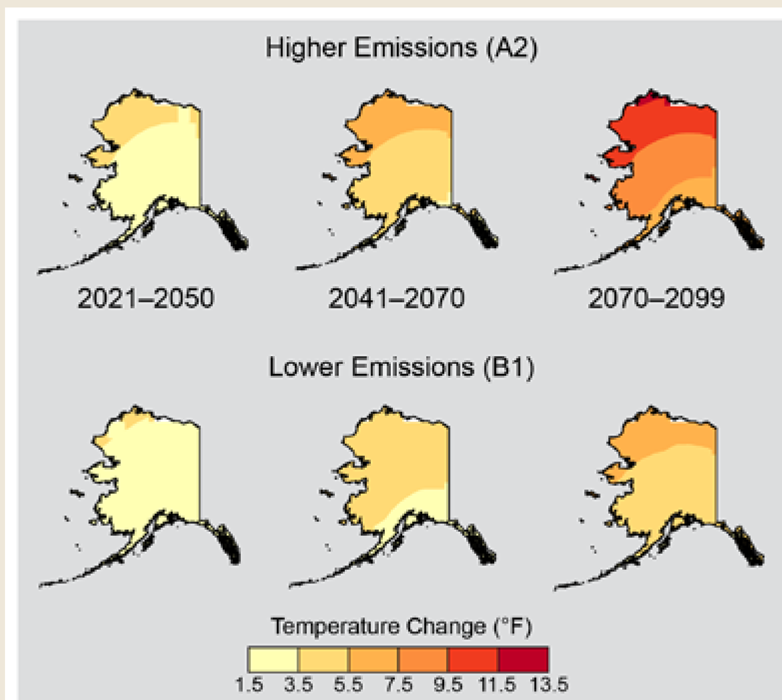


Figure 22.1. Northern latitudes are warming faster than more temperate regions, and Alaska has already warmed much faster than the rest of the country. Maps show changes in temperature, relative to 1971-1999, projected for Alaska in the early, middle, and late parts of this century, if heat-trapping gas (also known as greenhouse gas) emissions continue to increase (higher emissions, A2), or are substantially reduced (lower emissions, B1). (Figure source: adapted from Stewart et al. 2013[7]).

Changes in dates of snowmelt and freeze-up would influence seasonal migration of birds and other animals, increase the likelihood and rate of northerly range expansion of native and non-native species, alter the habitats of both ecologically important and endangered species, and affect ocean currents.[16]

Key Message 1: Disappearing Sea Ice

Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Arctic sea ice extent and thickness have declined substantially, especially in late summer (September), when there is now only about half as much sea ice as at the beginning of the satellite record in 1979 (Ch. 2: Our Changing Climate, Key Message 11).[17,18] The seven Septembers with the lowest ice extent all occurred in the past seven years. As sea ice declines, it becomes thinner, with less ice build-up over multiple years, and therefore more vulnerable to further melting.[18] Models that best match historical trends project northern waters that are virtually ice-free by late summer by the 2030s.[19,20] Within the general downward trend in sea ice, there will be time periods with both rapid ice loss and temporary recovery,[21] making it challenging to predict short-term changes in ice conditions.

Reductions in sea ice increase the amount of the sun's energy that is absorbed by the ocean. This leads to a self-reinforcing climate cycle, because the warmer ocean melts more ice, leaving more dark open water that gains even more heat. In autumn and winter, there is a strong release of this extra ocean heat back to the atmosphere. This is a key driver of the observed increases in air temperature in the Arctic.[23] This strong warming linked to ice loss can influence atmospheric circulation and patterns of precipitation, both within and beyond the Arctic (for example, Porter et al. 2012[24]). There is growing evidence that this has already occurred[25] through more evaporation from the ocean, which increases water vapor in the lower atmosphere[26] and autumn cloud cover west and north of Alaska.[27]

With reduced ice extent, the Arctic Ocean is more accessible for marine traffic, including trans-Arctic shipping, oil and gas

Declining Sea Ice Extent

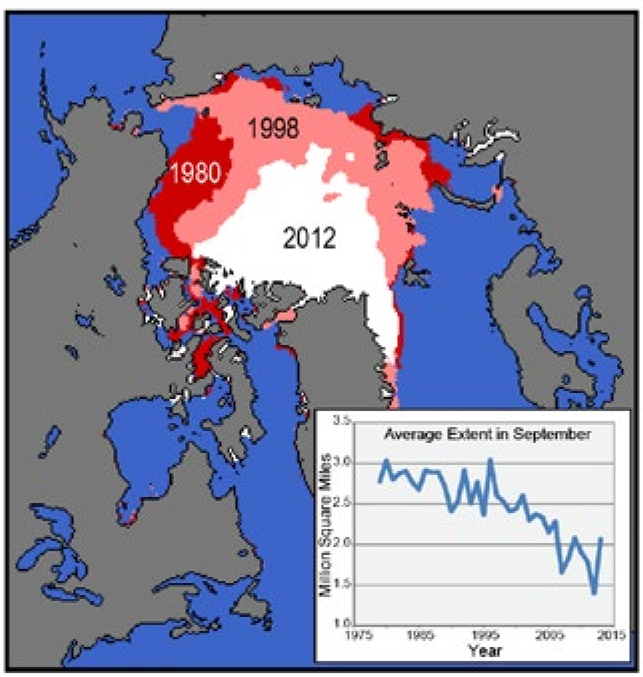


Figure 22.2. Average September extent of Arctic sea ice in 1980 (second year of satellite record and year of greatest September sea ice extent; outer red boundary), 1998 (about halfway through the time series; outer pink boundary) and 2012 (recent year of record and year of least September sea ice extent; outer white boundary). September is typically the month when sea ice is least extensive. Inset is the complete time series of average September sea ice extent (1979-2013). (Figure source: NSIDC 2012; Data from Fetterer et al. 2013[22]).

Sea Ice Loss Brings Big Changes to Arctic Life

Figure 22. 3. Reductions in sea ice alter food availability for many species from polar bear to walrus, make hunting less safe for Alaska Native hunters, and create more accessibility for Arctic Ocean marine transport, requiring more Coast Guard coverage. (Photo credits: (top left) G. Carleton Ray; (bottom left) Daniel Glick; (right) Patrick Kelley).

exploration, and tourism.[28] This facilitates access to the substantial deposits of oil and natural gas under the seafloor in the Beaufort and Chukchi seas, as well as raising the risk to people and ecosystems from oil spills and other drilling and maritime-related accidents. A seasonally ice-free Arctic Ocean also increases sovereignty and security concerns as a result of potential new international disputes and increased possibilities for marine traffic between the Pacific and Atlantic Oceans.[10]

Polar bears are one of the most sensitive Arctic marine mammals to climate warming because they spend most of their lives on sea ice.[29] Declining sea ice in northern Alaska is associated with smaller bears, probably because of less successful hunting of seals, which are themselves ice-dependent and so are projected to decline with diminishing ice and snow cover.[30] Although bears can give birth to cubs on sea ice, increasing numbers of female bears now come ashore in Alaska in the summer and fall[31] and den on land.[32] In Hudson Bay, Canada, the most studied population in the Arctic, sea ice is now absent for three weeks longer than just a few decades ago, resulting in less body fat, reduced survival of both the youngest and oldest bears,[33] and a population now estimated to be in decline[34] and projected to be in jeopardy.[35] Similar polar bear population declines are projected for the Beaufort Sea region.[36]

Walrus depend on sea ice as a platform for giving birth, nursing, and resting between dives to the seafloor, where they feed.[37] In recent years, when summer sea ice in the Chukchi Sea retreated over waters that were too deep for walrus to feed,[38] large numbers of walrus abandoned the ice and came ashore. The high concentration of animals results in increased competition for food and can lead to stampedes when animals are startled, resulting in trampling of calves.[39] This movement to land first occurred in 2007 and has happened three times since then, suggesting a threshold change in walrus ecology.

Living on the Front Lines of Climate Change

"Not that long ago the water was far from our village and could not be easily seen from our homes. Today the weather is changing and is slowly taking away our village. Our boardwalks are warped, some of our buildings tilt, the land is sinking and falling away, and the water is close to our homes. The infrastructure that supports our village is compromised and affecting the health and well-being of our community members, especially our children."

– Alaska Department of Commerce and Community and Economic Development, 2012[44]

Newtok, a Yup'ik Eskimo community on the seacoast of western Alaska, is on the front lines of climate change. Between October 2004 and May 2006, three storms accelerated the erosion and repeatedly "flooded the village water supply, caused raw sewage to be spread throughout the community, displaced residents from homes, destroyed subsistence food storage, and shut down essential utilities."[45] The village landfill, barge ramp, sewage treatment facility, and fuel storage facilities were destroyed or severely damaged.[46] The loss of the barge landing, which delivered most supplies and heating fuel, created a fuel crisis. Saltwater is intruding into the community water supply. Erosion is projected to reach the school, the largest building in the community, by 2017.

Recognizing the increasing danger from coastal erosion, Newtok has worked for a generation to relocate to a safer location. However, current federal legislation does not authorize federal or state agencies to assist communities in relocating, nor does it authorize them to repair or upgrade storm-damaged infrastructure in flood-prone locations like Newtok.[42] Newtok therefore cannot safely remain in its current location nor can it access public funds to adapt to climate change through relocation.

Newtok's situation is not unique. At least two other Alaskan communities, Shishmaref and Kivalina, also face immediate threat from coastal erosion and are seeking to relocate, but have been unsuccessful in doing so. Many of the world's largest cities are coastal and are also exposed to climate change induced flood risks.[47]

Newtok, Alaska

Figure 22.4. Residents in Newtok, Alaska are living with the effects of climate change, with thawing permafrost, tilting houses, sinking boardwalks, in conjunction with aging fuel tanks and other infrastructure that cannot be replaced because of laws that prevent public investment in flood-prone localities. (Photo credit: F. S. Chapin III).

With the late-summer ice edge located farther north than it used to be, storms produce larger waves and more coastal erosion.[10] An additional contributing factor is that coastal bluffs that were "cemented" by ice-rich permafrost are beginning to thaw in response to warmer air and ocean waters, and are therefore more vulnerable to erosion.[40] Standard defensive adaptation strategies to protect coastal communities from erosion, such as use of rock walls, sandbags, and riprap, have been largely unsuccessful.[41] Several coastal communities are seeking to relocate to escape erosion that threatens infrastructure and services but, because of high costs and policy constraints on use of federal funds for community relocation, only one Alaskan village has begun to relocate (see also Ch. 12: Indigenous Peoples).[42,43]

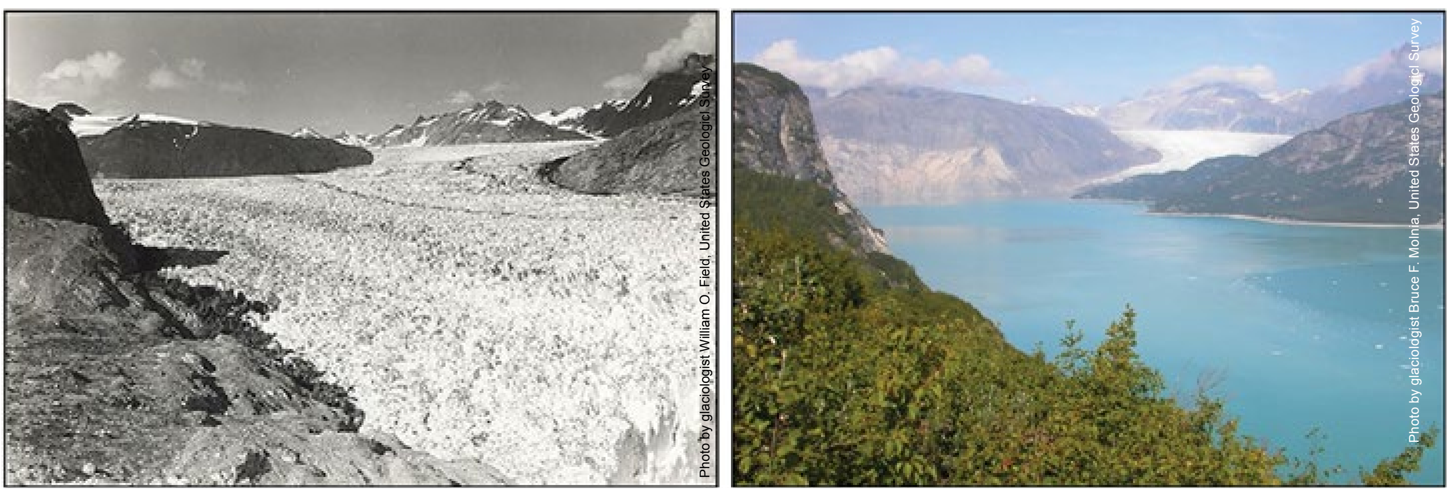
Key Message 2: Shrinking Glaciers

Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.

Alaska is home to some of the largest glaciers and fastest loss of glacier ice on Earth.[48,49,50] This rapid ice loss is primarily a result of rising temperatures (for example, Arendt et al. 2002, 2009[51,52,53]; Ch. 2: Our Changing Climate, Key Message 11). Loss of glacial volume in Alaska and neighboring British Columbia, Canada, currently contributes 20% to 30% as much surplus freshwater to the oceans as does the Greenland Ice Sheet – about 40 to 70 gigatons per year,[49,54,55,56] comparable to 10% of the annual discharge of the Mississippi River.[57] Glaciers continue to respond to climate warming for years to decades after warming ceases, so ice loss is expected to continue, even if air temperatures were to remain at current levels. The global decline in glacial and ice-sheet volume is predicted to be one of the largest contributors to global sea level rise during this century (Ch. 2: Our Changing Climate, Key Message 10).[58,59]

Water from glacial landscapes is also recognized as an important source of organic carbon,[60,61] phosphorus,[62] and iron[63] that contribute to high coastal productivity, so changes in these inputs could alter critical nearshore fisheries.[61,64]

Glaciers supply about half of the total freshwater input to the Gulf of Alaska.[65] Glacier retreat currently increases river discharge and hydropower potential in south central and southeast Alaska, but over the longer term might reduce water input to reservoirs and therefore hydropower resources.[3]



On the left is a photograph of Muir Glacier in Alaska taken on August 13, 1941; on the right, a photograph taken from the same vantage point on August 31, 2004. Total glacial mass has declined sharply around the globe, adding to sea level rise. (Left photo by glaciologist William O. Field; right photo by geologist Bruce F. Molnia of the United States Geological Survey.)

Key Message 3: Thawing Permafrost

Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.

Alaska differs from most of the rest of the U.S. in having permafrost – frozen ground that restricts water drainage and therefore strongly influences landscape water balance and the design and maintenance of infrastructure. Permafrost near the Alaskan Arctic coast has warmed 4°F to 5°F at 65 foot depth[66,67] since the late 1970s and 6°F to 8°F at 3.3 foot depth since the mid-1980s.[68] In Alaska, 80% of land is underlain by permafrost, and of this, more than 70% is vulnerable to subsidence upon thawing because of ice content that is either variable, moderate, or high.[69] Thaw is already occurring in interior and southern Alaska and in northern Canada, where permafrost temperatures are near the thaw point.[70] Models project that permafrost in Alaska will continue to thaw,[71,72] and some models project that near-surface permafrost will be lost entirely from large parts of Alaska by the end of the century.[73]

Uneven sinking of the ground in response to permafrost thaw is estimated to add between $3.6 and $6.1 billion (10% to 20%) to current costs of maintaining public infrastructure such as buildings, pipelines, roads, and airports over the next 20 years.[74] In rural Alaska, permafrost thaw will likely disrupt community water supplies and sewage systems,[75,76,77] with negative effects on human health.[78] The period during which oil and gas exploration is allowed on tundra has decreased by 50% since the 1970s as a result of permafrost vulnerability.[11]

On average, lakes have decreased in area in the last 50 years in the southern two-thirds of Alaska,[80,81,82] due to a combination of permafrost thaw, greater evaporation in a warmer climate, and increased soil organic accumulation during a longer season for plant growth. In some places, however, lakes are getting larger because of lateral permafrost degradation.[81] Future permafrost thaw will likely increase lake area in areas of continuous permafrost and decrease lake area in places where the permafrost zone is more fragmented.[71]

A continuation of the current drying of Alaskan lakes and wetlands could affect waterfowl management nationally because Alaska accounts for 81% of the National Wildlife Refuge System and provides breeding habitat for millions of migratory birds that winter in more southerly regions of North America and on other continents.[83] Wetland loss would also reduce waterfowl harvest in Alaska, where it is an important food source for Alaska Natives and other rural residents.

Both wetland drying and the increased frequency of warm dry summers and associated thunderstorms have led to more large fires in the last ten years than in any decade since record-keeping began in the 1940s.[14] In Alaskan tundra, which was too cold and wet to support extensive fires for approximately the last 5,000 years,[84] a single large fire in 2007 released as much carbon to the atmosphere as had been absorbed by the entire circumpolar Arctic tundra during the previous quarter-century.[85] Even if climate warming were curtailed by reducing heat-trapping gas (also known as greenhouse gas) emissions (as in the B1 scenario), the annual area burned in Alaska is pro-

The Big Thaw

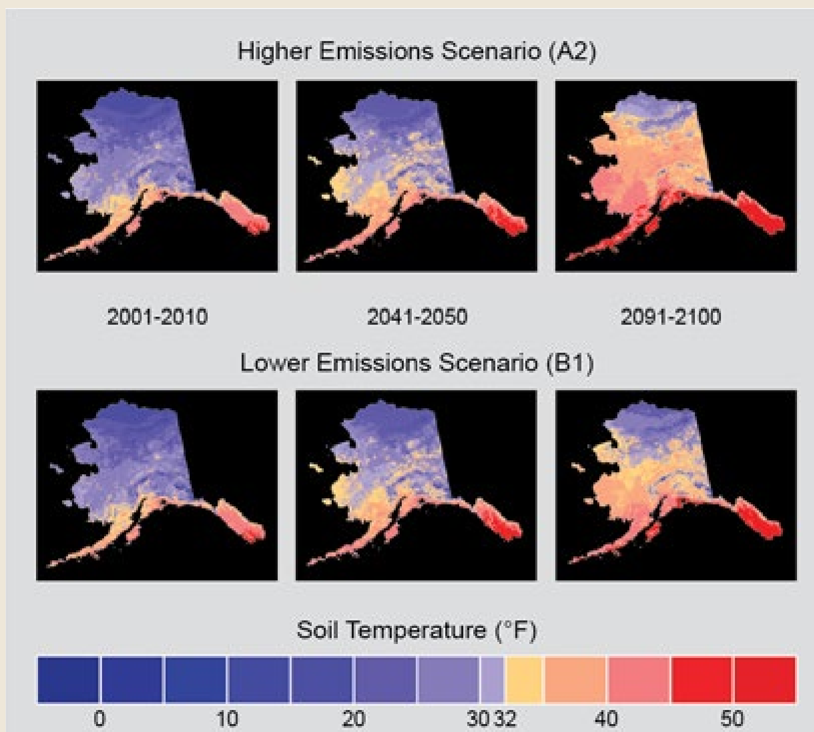


Figure 22.5. Projections for average annual ground temperature at a depth of 3.3 feet over time if emissions of heat-trapping gases continue to grow (higher emissions scenario, A2), and if they are substantially reduced (lower emissions scenario, B1). Blue shades represent areas below freezing at a depth of 3.3 feet, and yellow and red shades represent areas above freezing at that depth, based on the GIPL 1.0 model. (Figure source: Permafrost Lab, Geophysical Institute, University of Alaska Fairbanks).

jected to double by mid-century and to triple by the end of the century,[86] thus fostering increased emissions of heat-trapping gases, higher temperatures, and increased fires. In addition, thick smoke produced in years of extensive wildfire represents a human health risk (Ch. 9: Human Health). More extensive and severe wildfires could shift the forests of Interior Alaska during this century from dominance by spruce to broadleaf trees for the first time in the past 4,000 to 6,000 years.[87,88]

Wildfire has mixed effects on habitat. It generally improves habitat for berries, mushrooms, and moose,[58,89] but reduces winter habitat for caribou because lichens, a key winter food source for caribou, require 50 to 100 years to recover after wildfire.[90] These habitat changes are nutritionally and culturally significant for Alaska Native Peoples.[89,91] In addition, exotic plant species that were introduced along roadways are now spreading onto river floodplains and recently burned forests,[92] potentially changing the suitability of these lands for timber production and wildlife. Some invasive species are toxic to moose, on which local people depend for food.[93]

Changes in terrestrial ecosystems in Alaska and the Arctic may be influencing the global climate system. Permafrost soils throughout the entire Arctic contain almost twice as much carbon as the atmosphere.[94] Warming and thawing of these soils increases the release of carbon dioxide and methane through increased decomposition. Thawing permafrost also delivers organic-rich soils to lake bottoms, where decomposition in the absence of oxygen releases additional methane.[95] Extensive wildfires also release carbon that contributes to climate warming.[86,96] The capacity of the Yukon River Basin in Alaska and adjacent Canada to store carbon has been substantially weakened since the 1960s by the combination of warming and thawing of permafrost and by increased wildfire.[97] Expansion of tall shrubs and trees into tundra makes the surface darker and rougher, increasing absorption of the sun's energy and further contributing to warming.[98] This warming is likely stronger than the potential cooling effects of increased carbon dioxide uptake associated with tree and shrub expansion.[99] The shorter snow-covered seasons in Alaska further increase energy absorption by the land surface, an effect only slightly offset by the reduced energy absorption of highly reflective post-fire snow-covered landscapes.[99] This spectrum of changes in Alaskan and other high-latitude terrestrial ecosystems jeopardizes efforts by society to use ecosystem carbon management to offset fossil fuel emissions.[94,100]

Mounting Expenses from Permafrost Thawing

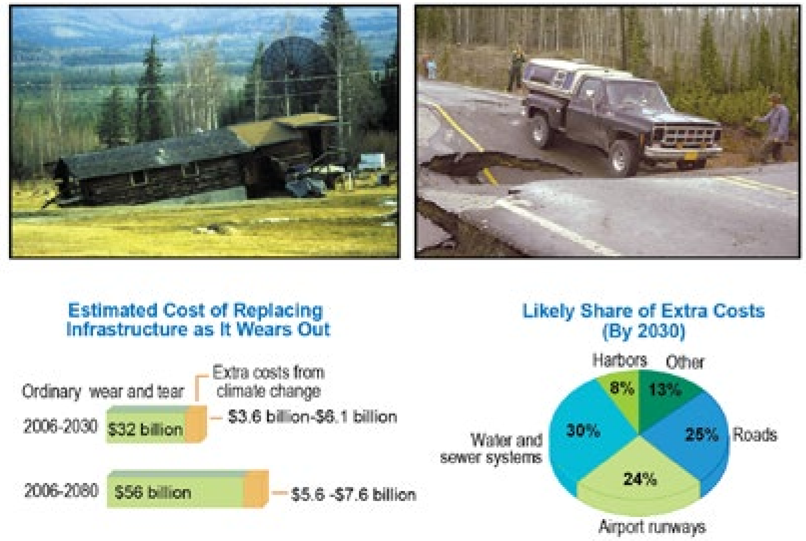


Figure 22.6. Effects of permafrost thaw on houses in interior Alaska (2001, top left), roads in eastern Alaska (1982, top right), and the estimated costs (with and without climate change) of replacing public infrastructure in Alaska, assuming a mid-range emissions scenario (A1B, with some decrease from current emissions growth trends). (Photo credits: (top left) Larry Hinzman; (top right) Joe Moore. Figure source: adapted from Larsen and Goldsmith 2007[79]).

Drying Lakes and Changing Habitat

Figure 22.7. Progressive drying of lakes in northern forest wetlands in the Yukon Flats National Wildlife Refuge, Alaska. Foreground orange area was once a lake. Mid-ground lake once extended to the shrubs. (Photo credit: May-Le Ng).

Key Message 4: Changing Ocean Temperatures and Chemistry

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes interact to affect the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence.[101,102,103] These changes have allowed some near-surface fish species such as salmon to expand their ranges northward along the Alaskan coast.[104] In addition, non-native species are invading Alaskan waters more rapidly, primarily through ships releasing ballast waters and bringing southerly species to Alaska.[10,105] These species introductions could affect marine ecosystems, including the feeding relationships of fish important to commercial and subsistence fisheries.

Overall habitat extent is expected to change as well, though the degree of the range migration will depend upon the life history of particular species. For example, reductions in seasonal sea ice cover and higher surface temperatures may open up new habitat in polar regions for some important fish species, such as cod, herring, and pollock.[106] However, continued presence of cold bottom-water temperatures on the Alaskan continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea off northwestern Alaska.[107] In addition, warming may cause reductions in the abundance of some species, such as pollock, in their current ranges in the Bering Sea[108] and reduce the health of juvenile sockeye salmon, potentially resulting in decreased overwinter survival.[109] If ocean warming continues, it is unlikely that current fishing pressure on pollock can be sustained.[110] Higher temperatures are also likely to increase the frequency of early Chinook salmon migrations, making management of the fishery by multiple user groups more challenging.[111]

The changing temperature and chemistry of the Arctic Ocean and Bering Sea are likely changing their role in global ocean circulation and as carbon sinks for atmospheric CO_2 respectively, although the importance of these changes in the global carbon budget remains unresolved. The North Pacific Ocean is particularly susceptible to ocean acidification (see also Ch. 2: Our Changing Climate, Key Message 12; Ch. 24: Oceans).[112] Acidifying changes in ocean chemistry have potentially widespread impacts on the marine food web, including commercially important species.

Ocean Acidification in Alaska

Ocean waters globally have become 30% more acidic due to absorption of large amounts of human-produced carbon dioxide (CO_2) from the atmosphere. This CO_2 interacts with ocean water to form carbonic acid that lowers the ocean's pH (ocean acidification). The polar ocean is particularly prone to acidification because of low temperature[113,114] and low salt content, the latter resulting from the large freshwater input from melting sea ice[115] and large rivers. Acidity reduces the capacity of key plankton species and shelled animals to form and maintain shells and other hard parts, and therefore alters the food available to important fish species.[113,116] The rising acidity will have particularly strong societal effects on the Bering Sea on Alaska's west coast because of its high-productivity commercial and subsistence fisheries.[102,117]

Shelled pteropods, which are tiny planktonic snails near the base of the food chain, respond quickly to acidifying conditions and are an especially critical link in high-latitude food webs, as commercially important species such as pink salmon depend heavily on them for food.[118] A 10% decrease in the population of pteropods could mean a 20% decrease in an adult pink salmon's body weight.[119] Pteropod consumption by juvenile pink salmon in the northern Gulf of Alaska varied 45% between 1999 and 2001, although the reason for this variation is unknown.[120]

At some times of year, acidification has already reached a critical threshold for organisms living on Alaska's continental shelves.[121] Certain algae and animals that form shells (such as clams, oysters, and crab) use carbonate minerals (aragonite and calcite) that dissolve below that threshold. These organisms form a crucial component of the marine food web that sustains life in the rich waters off Alaska's coasts. In addition, Alaska oyster farmers are now indirectly affected by ocean acidification impacts farther south because they rely on oyster spat (attached oyster larvae) from Puget Sound farmers who are now directly affected by the recent upwelling of acidic waters along the Washington and Oregon coastline (Ch. 24: Oceans; Ch. 21: Northwest).[122]

Key Message 5: Native Communities

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

With the exception of oil-producing regions in the north, rural Alaska is one of the most extensive areas of poverty in the U.S. in terms of household income, yet residents pay the highest prices for food and fuel.[123] Alaska Native Peoples, who are the most numerous residents of this region, depend economically, nutritionally, and culturally on hunting and fishing for their livelihoods.[124,125,126] Hunters speak of thinning sea and river ice that makes harvest of wild foods more dangerous,[127] changes to permafrost that alter spring run-off patterns, a northward shift in seal and fish species, and rising sea levels with more extreme tidal fluctuations (see Ch. 12: Indigenous Peoples).[128,129] Responses to these changes are often constrained by regulations.[77,129] Coastal erosion is destroying infrastructure. Impacts of climate change on river ice dynamics and spring flooding are threats to river communities but are complex, and trends have not yet been well documented.[130]

Major food sources are under stress due to many factors, including lack of sea ice for marine mammals.[131] Thawing of near-surface permafrost beneath lakes and ponds that provide drinking water cause food and water security challenges for villages. Sanitation and health problems also result from deteriorating water and sewage systems, and ice cellars traditionally used for storing food are thawing (see also Ch. 12: Indigenous Peoples).[75,78] Warming also releases human-caused pollutants, such as poleward-transported mercury and organic pesticides, from thawing permafrost and brings new diseases to Arctic plants and animals, including subsistence food species, posing new health challenges, especially to rural communities.[132] Positive health effects of warming include a longer growing season for gardening and agriculture.[10,133]

Development activities in the Arctic (for example, oil and gas, minerals, tourism, and shipping) are of concern to Indigenous communities, from both perceived threats and anticipated benefits.[126] Greater levels of industrial activity might alter the distribution of species, disrupt subsistence activities, increase the risk of oil spills, and create various social impacts. At the same time, development provides economic opportunities, if it can be harnessed appropriately.[134]

Alaska Native Elders say, "We must prepare to adapt." However, the implications of this simple instruction are multi-faceted. Adapting means more than adjusting hunting technologies and foods eaten. It requires learning how to garner information from a rapidly changing environment. Permanent infrastructure and specified property rights increasingly constrain people's ability to safely use their environment for subsistence and other activities.

Traditional knowledge now facilitates adaptation to climate change as a framework for linking new local observations with western science.[124,135] The capacity of Alaska Natives to survive for centuries in the harshest of conditions reflects their resilience.[91] Communities must rely not only on improved knowledge of changes that are occurring, but also on support from traditional and other institutions – and on strength from within – in order to face an uncertain future.[124]

Alaska Coastal Communities Damaged

Figure 22.8: One effect of the reduction in Alaska sea ice is that storm surges that used to be buffered by the ice are now causing more shoreline damage. Photos show infrastructure damage from coastal erosion in Tuntutuliak (left) and Shishmaref, Alaska (right). (Photo credits: (left) Alaska Department of Environmental Conservation; (right) Ned Rozell).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for developing key messages
A central component of the assessment process was the Alaska Regional Climate assessment workshop that was held September 12-15, 2012, in Anchorage with approximately 20 attendees; it began the process leading to a foundational Technical Input Report (TIR).[10] The report consists of 148 pages of text, 45 figures, 8 tables, and 27 pages of references. Public and private citizens or institutions were consulted and engaged in its preparation and expert review by the various agencies and non-governmental organizations (NGOs) represented by the 11-member TIR writing team. The key findings of the report were presented at the Alaska Forum on the Environment and in a regularly scheduled, monthly webinar by the Alaska Center for Climate Assessment and Policy, with feedback then incorporated into the report.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful expert review of the foundational TIR[10] and of approximately 85 additional technical inputs provided by the public, as well as the other published literature and professional judgment. These discussions were followed by expert deliberation of draft key messages by the writing team in a face-to-face meeting before each key message was selected for inclusion in the Report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities" (Ch. 26: Decision Support).

Key message #1 Traceable Account

Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Description of evidence base
The key message and supporting chapter text summarize extensive evidence documented in the Alaska TIR.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Although various models differ in the projected rate of sea ice loss, more recent CMIP5 models[20] that most accurately reconstruct historical sea ice loss project that late-summer sea ice will virtually disappear by the 2030s, leaving only remnant sea ice.

Evidence is strong about the impacts of sea ice loss.[10] Because the sea ice cover plays such a strong role in human activities and Arctic ecosystems, loss of the ice cover is nearly certain to have substantial impacts.[17]

New information and remaining uncertainties
Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

Evidence from improved models (for example, Wang and Overland 2012[20]) and updated observational data from satellite, especially new results, clearly show rapid decline in not only extent but also mass and thickness of multi-year ice,[18] information that was not available in prior assessments.

Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining and that, if heat-trapping gas concentrations continue to rise, an essentially ice-free summer Arctic ocean will be realized before mid-century. However, there remains uncertainty in the rate of sea ice loss, with the models that most accurately project historical sea ice trends currently suggesting nearly ice-free conditions sometime between 2021 and 2043 (median 2035).[20] Uncertainty across all models stems from a combination of large differences in projections among different climate models, natural climate variability, and uncertainty about future rates of fossil fuel emissions.

Ecosystems: There is substantial new information that ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes are affecting the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence.[101,102] However, the relative importance of these potential causes of change is highly uncertain.

Offshore oil and gas development: A key uncertainty is the price of fossil fuels. Viable avenues for improving the information base include determining the primary causes of variation among different climate models and determining which climate models exhibit the best ability to reproduce the observed rate of sea ice loss.

Coastal erosion: There is new information that lack of sea ice causes storms to produce larger waves and more coastal erosion.[10] An additional contributing factor is that coastal bluffs that were "cemented" by permafrost are beginning to thaw in response to warmer air and ocean waters, and are therefore more vulnerable to erosion.[40] Standard defensive adaptation strategies to protect coastal communities from erosion such as use of rock walls, sandbags, and riprap have been largely unsuccessful.[41] There remains considerable uncertainty, however, about the spatial patterns of future coastal erosion.

Assessment of confidence based on evidence
Given the evidence base and remaining uncertainties:

Very high confidence for summer sea ice decline. **High** confidence for summer sea ice disappearing by mid-century.

Very high confidence for altered marine ecosystems, greater ship access, and increased vulnerability of communities to coastal erosion.

High confidence regarding offshore development opportunity.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.

Description of evidence base
The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that glaciers in Alaska and British Columbia are shrinking is strong and is based on field studies,[56] energy balance models,[59] LIDAR remote sensing,[51,52] and satellite data, especially new lines of evidence from the Gravity Recovery and Climate Experiment (GRACE) satellite.[48,52,55]

Evidence is also strong that Alaska ice mass loss contributes to global sea level rise,[58] with latest results permitting quantitative evaluation of losses globally.[49]

Numerous peer-reviewed publications describe implications of recent increases, but likely longer-term declines, in water input from glacial rivers to reservoirs and therefore hydropower resources.[3,10,65]

Glacial rivers account for 47% of the freshwater input to the Gulf of Alaska[65] and are an important source of organic carbon,[60,61] phosphorus,[62] and iron[63] that contribute to the high productivity of near-shore fisheries.[61,64] Therefore, it is projected that the changes in discharge of glacial rivers will affect ocean circulation patterns and major U.S. and locally significant fisheries.

New information and remaining uncertainties
Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

As noted above, major advances from GRACE and other datasets now permit analyses of glacier mass loss that were not possible previously.

Key uncertainties remain related to large year-to-year variation, the spatial distribution of snow accumulation and melt, and the quantification of glacier calving into the ocean and lakes. Although most large glaciated areas of the state are regularly measured observationally, extrapolation to unmeasured areas carries uncertainties due to large spatial variability.

Although there is broad agreement that near-shore circulation in the Gulf of Alaska is influenced by the magnitude of freshwater inputs, little is known about the mechanisms by which near-term increases and subsequent longer-term decreases in glacier runoff (as the glaciers disappear) will affect the structure of the Alaska Coastal Current and smaller-scale ocean circulation, both of which have feedback on fisheries.

The magnitude and timing of effects on hydropower production depend on changes in glacial mass, as described above.

Assessment of confidence based on evidence

High confidence that glacier mass loss in Alaska and British Columbia is high, contributing 20% to 30% as much to sea level rise as does shrinkage of the Greenland Ice Sheet.

High confidence that due to glacier mass loss there will be related impacts on hydropower production, ocean circulation, fisheries, and global sea level rise.

Key message #3 Traceable Account

Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Previous evidence that permafrost is warming[66] has been confirmed and enhanced by more recent studies.[70] The most recent modeling efforts (for example, Avis et al. 2011; Jafarov et al. 2012[71,73]) extend earlier results[72] and project that permafrost will be lost from the upper few meters from large parts of Alaska by the end of this century.

Evidence that permafrost thaw leads to drier landscapes[81,82] is beginning to accumulate, especially as improved remote sensing tools are applied to assess more remote regions.[71]

Satellite data has expanded the capacity to monitor wildfire across the region, providing additional evidence of wildfire extent.[87] This new evidence has led to increased study that is beginning to reveal impacts on ecosystems and wildlife habitat, but much more work is needed to understand the extent of natural resilience.

Impacts of permafrost thaw on the maintenance of infrastructure[11,74,75,76,77] is currently moderate but rapidly accumulating. Evidence that permafrost thaw will jeopardize efforts to offset fossil fuel emissions is suggestive (Ch. 2: Our Changing Climate).[94,100]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

This evidence included results from improved models and updated observational data. The assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm the relevance and significance of the key message for local decision-makers.

Key uncertainties involve: 1) the degree to which increases in evapotranspiration versus permafrost thaw are leading to drier landscapes; 2) the degree to which it is these drier landscapes associated with permafrost thaw, versus more severe fire weather associated with climate change, that is leading to more wildfire; 3) the degree to which the costs of the maintenance of infrastructure are associated with permafrost thaw caused by climate change versus disturbance of permafrost due to other human activities; and 4) the degree to which climate change is causing Alaska to be a sink versus a source of greenhouse gases to the atmosphere.

Assessment of confidence based on evidence

Very high confidence that permafrost is warming.

High confidence that landscapes in interior Alaska are getting drier, although the relative importance of different mechanisms is not completely clear.

Medium confidence that thawing permafrost results in more wildfires. There is **high** confidence that wildfires have been increasing in recent decades, even if it is not clear whether permafrost thaw or hotter and drier weather is more important.

High confidence that climate change will lead to increased maintenance costs in future decades. **Low** confidence that climate change has led to increased maintenance costs of infrastructure in recent decades.

Very high confidence that ecological changes will cause Alaska to become a source of greenhouse gases to the atmosphere, even though evidence that Alaska is currently a carbon source is only suggestive.

Key message #4 Traceable Account

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10]

Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe evidence that ocean temperatures are rising and ocean chemistry, especially pH, is changing.[10] New observational data from buoys and ships document increasing acidity and aragonite under-saturation (that is, the tendency of calcite and aragonite in shells to dissolve) in Alaskan coastal waters.

Accumulating strong evidence suggests that these changes in ocean temperature and chemistry, including pH, will likely affect major Alaska marine fisheries, although the relative importance of these changes and the exact nature of response of each fishery are uncertain.[101,102,103]

Alaska's commercial fisheries account for roughly 50 percent of the United States' total wild landings. Alaska led all states in both volume and ex-vessel value of commercial fisheries landings in 2009, with a total of 1.84 million metric tons worth $1.3 billion.[1]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

The new evidence included results from improved models and updated observational data. The assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm the relevance and significance of the key message for local decision-makers.

A key uncertainty is what the actual impacts of rising temperatures and changing ocean chemistry, including an increase in ocean acidification, will be on a broad range of marine biota and ecosystems. More monitoring is needed to document the extent and location of changes. Additional research is needed to assess how those changes will affect the productivity of key fishery resources and their food and prey base.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

High confidence of increased ocean temperatures and changes in chemistry.

Medium confidence that fisheries will be affected.

Key message #5 Traceable Account

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence exists in recorded local observational accounts as well as in the peer-reviewed scientific literature of the cumulative effects of climate-related environmental change on Native communities in Alaska; these effects combine with other socioeconomic stressors to strain rural Native communities (Ch. 12: Indigenous Peoples).[124,125,126,131] Increasing attention to impacts of climate change is revealing new aspects, such as impacts to health and hunter safety (for example, Baffrey and Huntington 2010; Brubaker et al. 2011[78,134]). There is also strong evidence for the cultural adaptive capacity of these communities and peoples over time.[91,130,135]

New information and remaining uncertainties

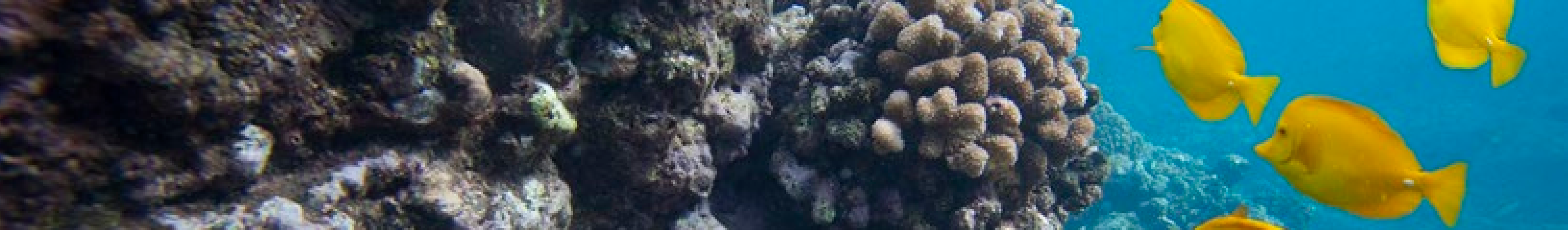
Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

The precise mechanisms by which climate change affects Native communities are poorly understood, especially in the context of rapid social, economic, and cultural change. Present day responses to environmental change are poorly documented. More research is needed on the ways that Alaska Natives respond to current biophysical climate change and to the factors that enable or constrain contemporary adaptation.

Alaska Native communities are already being affected by climate-induced changes in the physical and biological environment, from coastal erosion threatening the existence of some communities, to alterations in hunting, fishing, and gathering practices that undermine the intergenerational transfer of culture, skill, and wisdom. At the same time, these communities have a long record of adaptation and flexibility. Whether such adaptability is sufficient to address the challenges of climate change depends both on the speed of climate-induced changes and on the degree to which Native communities are supported rather than constrained in the adaptive measures they need to make.[124]

Assessment of confidence based on evidence

There is **high** confidence that cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.



CHAPTER 23
HAWAI‘I
AND U.S. AFFILIATED PACIFIC ISLANDS

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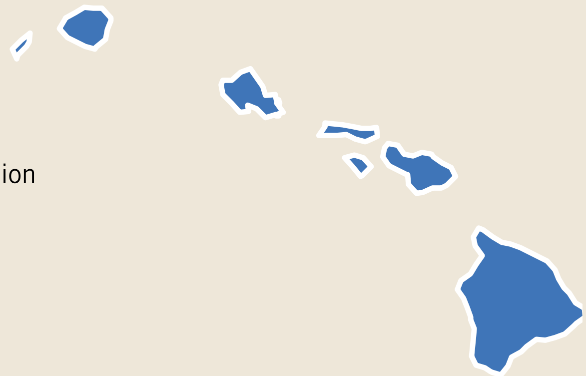

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

23 HAWAI‘I AND U.S. AFFILIATED PACIFIC ISLANDS

Key Messages

1. **Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.**
2. **Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.**
3. **Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.**
4. **Rising sea levels, coupled with high water levels caused by storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.**
5. **Mounting threats to food and water security, infrastructure, health, and safety are expected to lead to increasing human migration, making it increasingly difficult for Pacific Islanders to sustain the region’s many unique customs, beliefs, and languages.**

The U.S. Pacific Islands region (Figure 23.1) is vast, comprising more than 2,000 islands spanning millions of square miles of ocean. The largest group of islands in this region, the Hawaiian Archipelago, is located nearly 2,400 miles from any continental landmass, which makes it one of the most remote archipelagos on the globe.[1] The Hawaiian Islands support fewer than 2 million people, yet provide vital strategic capabilities to U.S. defense – and the islands’ biodiversity is important to the world. Hawai‘i and the U.S. affiliated Pacific Islands are at risk from climate changes that will affect nearly every aspect of life. Rising air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing baseflow in streams, rising sea levels, and changing ocean chemistry will affect ecosystems on land and in the oceans, as well as local communities, livelihoods, and cultures. Low islands are particularly at risk.


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The Pacific Islands include volcanic islands, islands of continental crust, atolls (formed by coral reefs), limestone islands, and islands of mixed geologic origin, with tremendous landscape diversity. In the Hawaiian High Islands, as many as 10 ecozones – from alpine systems to tropical rainforests – exist within a 25 mile span.[3,4] Isolation and landscape diversity in Hawai'i brings about some of the highest concentrations of native species, found nowhere else in the world.[4] Several U.S. Pacific Islands are marine biodiversity hotspots, with the greatest diversity found in the Republic of Palau, and the highest percentage of native reef fishes in Hawai'i.[5] These islands provide insights into evolution and adaptation, concepts important for predicting the impacts of climate change on ecosystems. Their genetic diversity also holds the potential for developing natural products and processes for biomedical and industrial use.

U.S. Pacific Islands Region

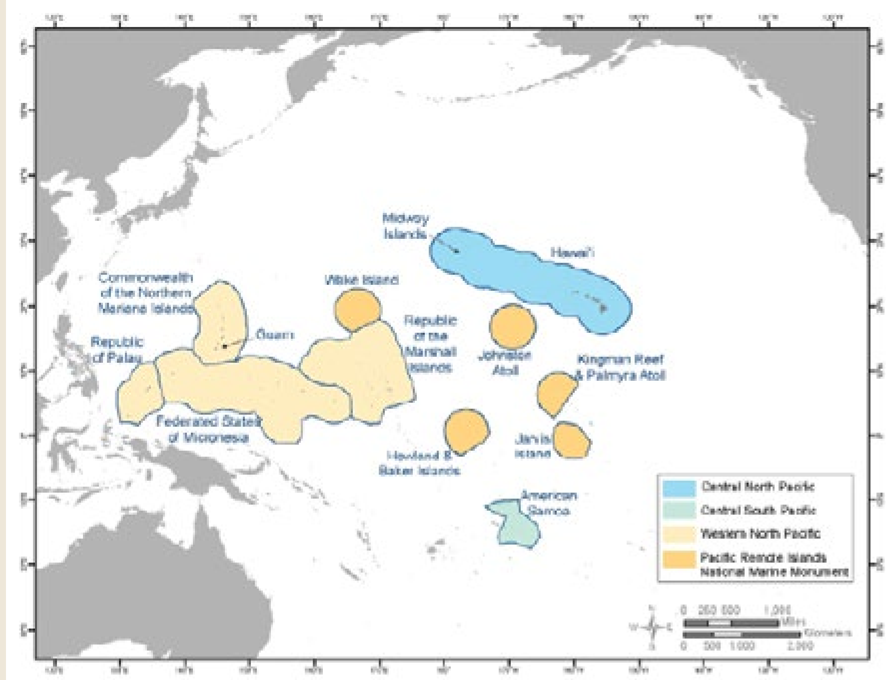

Figure 23.1. The U.S. Pacific Islands region includes our 50th state, Hawai'i, as well as the Territories of Guam, American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). Citizens of Guam and CNMI are U.S. citizens, and citizens of American Samoa are U.S. nationals. Through the Compacts of Free Association, citizens of RP, FSM, and RMI have the right to travel to the U.S. without visas to maintain "habitual residence" and to pursue education and employment. The map shows three sub-regions used in this assessment and the islands that comprise the Pacific Remote Islands National Monument. Shaded areas indicate each island's Exclusive Economic Zone (EEZ) (Figure source: Keener et al. 2012[2]).

The Pacific Islands region includes demographically, culturally, and economically varied communities of diverse indigenous Pacific Islanders, intermingled with immigrants from many countries. At least 20 languages are spoken in the region. Pacific Islanders recognize the value and relevance of their cultural heritage and systems of traditional knowledge; their laws emphasize the long-term multigenerational connection with their lands and resources.[6] Tourism contributes prominently to the gross domestic product of most island jurisdictions, as does the large U.S. military presence. Geographic remoteness means that the costs of air transport and shipping profoundly influence island economies. Natural resources are limited, with many communities relying on agriculture and ecosystems (such as coral reefs, open oceans, streams, and forests) for sustenance and revenue.

Key Message 1: Changes to Marine Ecosystems

Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.

Ocean temperatures in the Pacific region exhibit strong year-to-year and decadal fluctuations, but since the 1950s, they have also exhibited a warming trend, with temperatures from the surface to a depth of 660 feet rising by as much as 3.6°F.[7]

Future sea surface temperatures are projected to increase 1.1°F (compared to the 1990 levels) by 2030, 1.8°F by 2055, and 2.5°F by 2090 under a scenario that assumes substantial reductions in emissions (B1), or 1.7°F by 2030, 2.3°F by 2055, and 4.7°F by 2090 under a scenario that assumes continued increases in emissions (A2).[8]

Bleaching events (as a result of higher ocean temperatures) can weaken or kill corals. At least three mass bleaching episodes have occurred in the northwestern Hawaiian Islands in the last decade.[9] Incidences of coral bleaching have been recorded in

"High" and "Low" Pacific Islands Face Different Threats

Figure 23.2. The Pacific Islands include "high" volcanic islands, such as that on the left, that reach nearly 14,000 feet above sea level, and "low" atolls and islands, such as that on the right, that peak at just a few feet above present sea level. (Left) Ko'olau Mountains on the windward side of Oahu, Hawai'i (Photo credit: kstrebor via Flickr.com). (Right) Laysan Island, Papahānaumokuākea Marine National Monument (Photo credit: Andy Collins, NOAA).

Micronesia and American Samoa,[10] testing the resilience of these reefs. Coral disease outbreaks have also been reported in the Hawaiian archipelago,[11] American Samoa,[12,13] the Marshall Islands, and Palau,[14] correlated with periods of unusually high water temperatures.[15] Despite uncertainties, advanced modeling techniques project a large decline in coral cover in the Hawaiian Archipelago during this century. However, there are significant differences in the projected time frames and geographic distribution of these declines, even under a single climate change scenario.[16] By 2100, assuming ongoing increases in emissions of heat-trapping gases (A2 scenario), continued loss of coral reefs and the shelter they provide will result in extensive losses in both numbers and species of reef fishes.[17] Even with a substantial reduction in emissions (B1 scenario), reefs could be expected to lose as much as 40% of their reef-associated fish. Coral reefs in Hawai'i provide an estimated $385 million in goods and services annually,[18] which could be threatened by these impacts.

Ocean acidification is also taking place in the region, which adds to ecosystem stress from increasing temperatures. Ocean acidity has increased by about 30% since the pre-industrial era and is projected to further increase by 37% to 50% from present levels by 2100 (Ch. 2: Our Changing Climate, Key Message 12).[19] The amount of calcium carbonate, the biologically important mineral critical to reef-building coral and to calcifying algae, will decrease as a result of ocean acidification. By 2035 to 2060, levels of one form of the mineral (aragonite) are projected to decline enough to reduce coral growth and survival around the Pacific, with continuing declines thereafter.[20] Crustose coralline algae, an inconspicuous but important component of reefs that help reefs to form and that act as critical surfaces on which other living things grow, are also expected to exhibit reduced growth and survival.[21,22] Ocean acidification reduces the ability of corals to build reefs and also increases erosion,[23] leading to more fragile reef habitats. These changes are projected to have a strong negative impact on the econo-

El Niño and Other Patterns of Climate Variability

The Pacific region is subject to various patterns of climate variability. The effects of the El Niño-Southern Oscillation (ENSO) and other patterns of oceanic and atmospheric variability on the region are significant. They include large variations in sea surface temperatures, the strength and persistence of the trade winds, the position of jet streams and storm tracks, and the location and intensity of rainfall.[8,29,30] The ENSO-related extremes of El Niño and La Niña generally persist for 6 to 18 months and change phase roughly every 3 to 7 years.[8,31] The Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) are patterns that operate over even longer time horizons and also influence the weather and climate of the region.[31,32] Such dramatic short-term variability (the "noise") can obscure the long-term trend (the "signal").[33] Despite the challenges of distinguishing natural climate variability from climate change, there are several key indicators of observed change that serve as a basis for monitoring and evaluating future change.[2]

mies and well-being of island communities, with loss of coral biodiversity and reduced resilience.[24]

Similarly, there will be large impacts to the economically important tuna fishery in the Pacific Island region. Surface chlorophyll data obtained by satellites indicate less favorable conditions resulting in reduced productivity for tuna in the subtropical South and North Pacific[26] due to warming. This trend is projected to continue under future climate change.[27] One fishery model, coupled with a climate model, forecasts that the overall western and central Pacific fishery catch for skipjack tuna would initially increase by about 19% by 2035, though there would be no change for bigeye tuna. However, by 2100, skipjack catch would decline by 8% and bigeye catch would decline by 27% if emissions continue to rise (A2 scenario); geographic variations are projected within the region.[28]

These changes to both corals and fish pose threats to communities, cultures, and ecosystems of the Pacific Islands both directly through their impact on food security and indirectly through their impact on economic sectors including fisheries and tourism.

Increasing ocean temperature and acidity threaten coral reef ecosystems.

Increased Acidification Decreases Suitable Coral Habitat

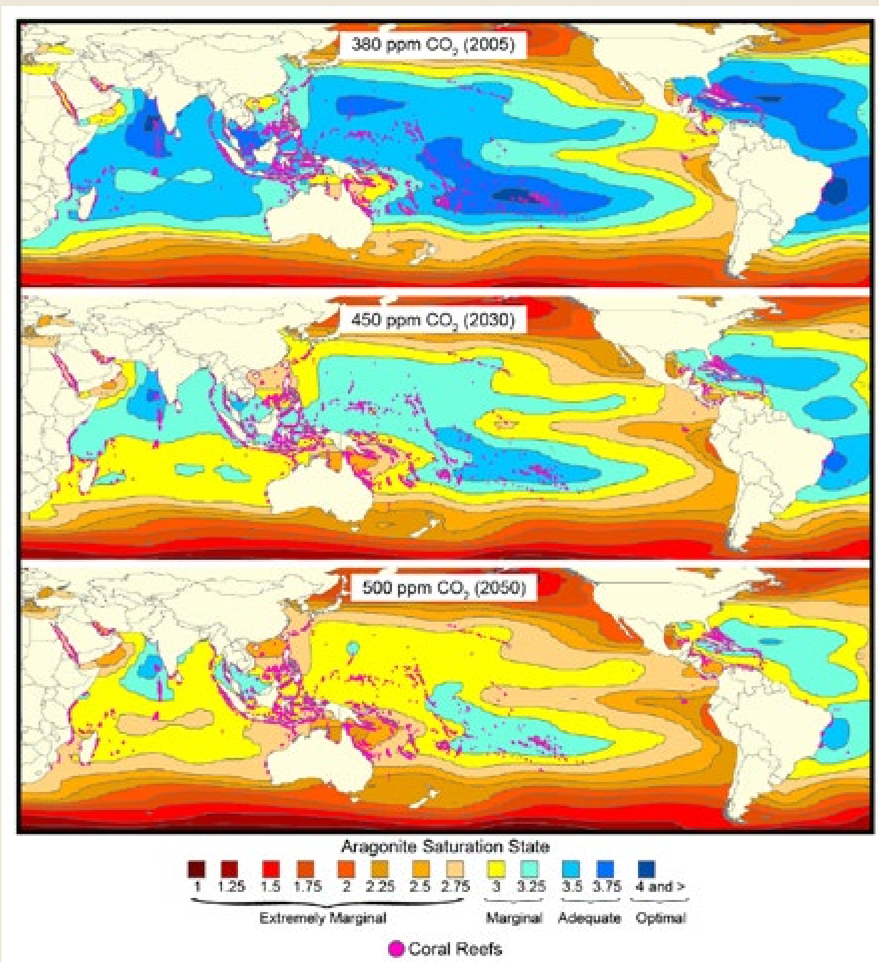

Figure 23.3. Ocean waters have already become more acidic from absorbing carbon dioxide from the atmosphere. As this absorption lowers pH, it reduces the amount of calcium carbonate, which is critical for many marine species to reproduce and grow. Maps show projections of the saturation state of aragonite (the form of calcium carbonate used by coral and many other species) if CO_2 levels were stabilized at 380 ppm (a level that has already been exceeded), 450 ppm (middle map), and 500 ppm (bottom map), corresponding approximately to the years 2005, 2030, and 2050, assuming a decrease in emissions from the current trend (scenario A1B). As shown on the maps, many areas that are adequate will become marginal. Higher emissions will lead to many more places where aragonite concentrations are "marginal" or "extremely marginal" in much of the Pacific. (Figure source: Burke et al. 2011[25]).

Key Message 2: Decreasing Freshwater Availability

Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.

In Hawai'i, average precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades, but with high variability due to cyclical climate patterns such as ENSO and the PDO (see "El Niño and other Patterns of Climate Variability").[34,35,36] For the Western North Pacific, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region, and slight upward trends in precipitation have been seen for the western-most islands with high ENSO-related variability.[7] In American Samoa, no trends in average rainfall are apparent, but there is very limited available data.[7,37]

Projections of precipitation are less certain than those for temperature.[2,38] For Hawai'i, a scenario based on statistical downscaling projects a 5% to 10% reduction for the wet season and a 5% increase in the dry season for the end of this century.[39] Projections for late this century from global models for the region give a range of results. Generally they predict annual rainfall to either change little or to increase by up to 5% for the main Hawaiian Islands and to change little or decrease up to 10% in the Northwestern Hawaiian Islands. They also project increases in the Micronesia region (Ch. 2: Our Changing Climate, Figure 2.6),[40] though there is low confidence in all these projections.

Climate change impacts on freshwater resources in the Pacific Islands will vary across the region. Different islands will be affected by different factors, including natural variability patterns that affect storms and precipitation (like El Niño and La Niña events), as well as climate trends that are strongly influenced by specific geographic locations. For example, surface air temperature has increased and is expected to continue to rise over the entire region.[41] In Hawai'i, the rate of increase has been greater at high elevations.[41] In Hawai'i and the Central North Pacific, projected annual surface air temperature increases range from 1.5°F by 2055 (relative to 1971-2000) under a scenario of substantial emissions reduction (B1), to 3.5°F assuming continued increases in emissions (A2).[40,42] In the Western North Pacific, the projected increases by 2055 are 1.9°F for the B1 scenario and 2.6°F for the A2 scenario.[8] In the central South Pacific, projected annual surface air temperature increases by 2055 are 1.9°F (B1) and 2.5°F (A2).[8]

On most islands, increased temperatures coupled with decreased rainfall and increased drought will reduce the amount of freshwater available for drinking and crop irrigation.[43] Climate change impacts on freshwater resources in the region will also vary because of differing island size and topography, which affect water storage capability and susceptibility to coastal flooding. Low-lying islands will be particularly vulnerable due to their small land mass, geographic isolation, limited potable water sources, and limited agricultural resources.[44] Also, as sea level rises over time, increasing saltwater intrusion from the ocean during storms will exacerbate the situation (Figure 23.6).[45,46] These are only part of a cascade of climate change related impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities.[47]

Observed Changes in Annual Rainfall in the Western North Pacific

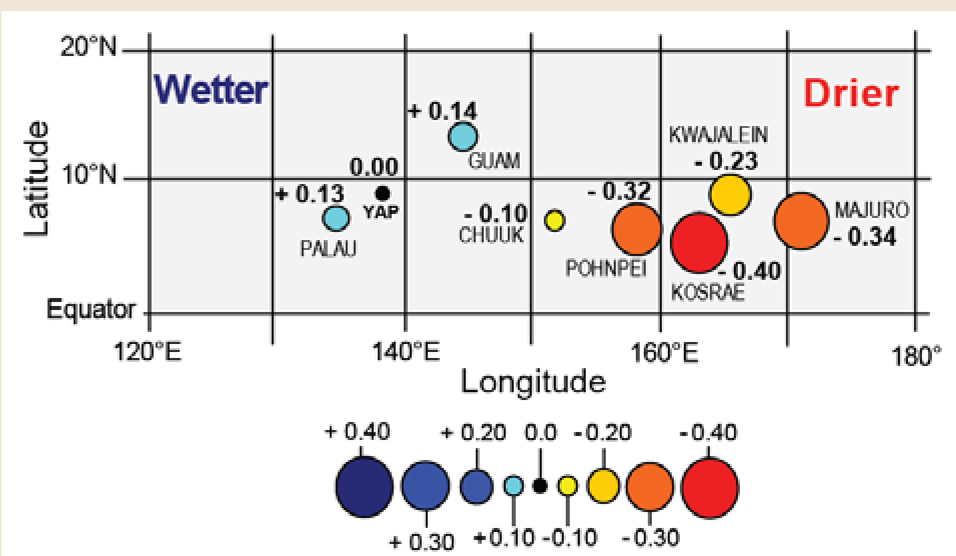

Figure 23.4. Islands in the western reaches of the Pacific Ocean are getting slightly more rainfall than in the past, while islands more to the east are getting drier (measured in change in inches of monthly rainfall per decade over the period 1950-2010). Darker blue shading indicates that conditions are wetter, while darker red shading indicates drier conditions. The size of the dot is proportional to the size of the trend on the inset scale. (Figure source: Keener et al. 2012[2]).

Key Message 3: Increased Stress on Native Plants and Animals

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Projected climate changes will significantly alter the distribution and abundance of many native marine, terrestrial, and freshwater species in the Pacific Islands. The vulnerability of coral reef and ocean ecosystems was discussed earlier. Land-based and freshwater species that exist in high-elevation ecosystems in high islands, as well as low-lying coastal ecosystems on all islands, are especially vulnerable. Existing climate zones on high islands are generally projected to shift upslope in response to climate change.[48] The ability of native species to adapt to shifting habitats will be affected by ecosystem discontinuity and fragmentation, as well as the survival or extinction of pollinators and seed dispersers. Some (perhaps many) invasive plant species will have a competitive edge over native species, as they disproportionately benefit from increased carbon dioxide, disturbances from extreme weather and climate events, and an ability to invade higher elevation habitats as climates warm.[49] Hawaiian high-elevation alpine ecosystems on Hawai'i and Maui islands are already beginning to show strong signs of higher temperatures and increased drought.[50] For example, the number of Haleakalā silversword, a rare plant that is an integral component of the alpine ecosystem in Haleakalā National Park in Maui and is found nowhere else on the planet, has declined dramatically over the past two decades.[51] Many of Hawai'i's native forest birds, marvels of evolution largely limited to high-elevation forests due to predators and diseases, are increasingly vulnerable as rising temperatures allow mosquitoes carrying diseases like avian malaria to thrive at higher elevations and thereby reduce the extent of safe bird habitat.[48,52]

Native Plants at Risk

Figure 23.5. Warming at high elevations could alter the distribution of native plants and animals in mountainous ecosystems and increase the threat of invasive species. The threatened, endemic 'ahinahina, or Haleakalā silversword (*Argyroxiphium sandwicense subsp. macrocephalum*), shown here in full bloom on Maui, Hawaiian Islands, is one example. (Photo credit: Forest and Kim Starr).

On high islands like Hawai'i, decreases in precipitation and baseflow are already indicating impacts on freshwater ecosystems and aquatic species.[35,37] Many Pacific Island freshwater fishes and invertebrates have oceanic larval stages in which they seasonally return to high island streams to aid reproduction.[53] Changes in stream flow and oceanic conditions that affect larval growth and survival will alter the ability of these species to maintain viable stream populations.

Key Message 4: Sea Level Rising

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Global average sea level has risen by about 8 inches since 1900,[54] with recent satellite observations indicating an increased rate of rise over the past two decades (1.3 inches per decade) (see also Ch. 2: Our Changing Climate, Key Message 10).[55] Recent regional sea level trends in the western tropical Pacific are higher[56,57] than the global average, due in part to changing wind patterns associated with natural climate variability.[58,59] Over this century, sea level in the Pacific is expected to rise at about the same rate as the projected increase in global average sea level, with regional variations associated with ocean circulation changes and the Earth's response to other large-scale changes, such as melting glaciers and ice sheets as well as changing water storage in lakes and reservoirs.[60,61] For the region, extreme sea level events generally occur when high tides combine with changes in water levels due to storms, ENSO (see "El Niño and other Patterns of Climate Variability"), and other variations.[54,55,56,57,58,59,60]

Rising sea levels will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, shallow coral reefs, sea grass beds, intertidal flats and mangrove forests, and other social, eco-

Saltwater Intrusion Destroys Crops

Figure 23.6. Taro crops destroyed by encroaching saltwater at Lukunoch Atoll, Chuuk State, FSM. Giant swamp taro is a staple crop in Micronesia that requires a two- to three-year growing period from initial planting to harvest. After a saltwater inundation from a storm surge or very high tide, it may take two years of normal rainfall to flush brackish water from a taro patch, resulting in a five-year gap before the next harvest if no further saltwater intrusion takes place. (Photo credit: John Quidachay, USDA Forest Service).

Residents of Low-lying Islands at Risk

Figure 23.7. Republic of the Marshall Islands, with a land area of just 1.1 square miles and a maximum elevation of 10 feet, may be among the first to face the possibility of climate change induced human migration as sea level continues to rise. (Photo credit: Darren Nakata).

nomic, and natural resources. Impacts will vary with location depending on how regional sea level variability combines with increases of global average sea level.[62] On low islands, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and periodic flooding increases the salinity of groundwater. Coastal and nearshore environments will progressively be affected as sea levels rise and high wave events alter low islands' size and shape. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10% to 20% in total regional mangrove area over the next century.[63] This would in turn reduce the nursery areas and feeding grounds for fish species, habitat for crustaceans and invertebrates, shoreline protection and wave dampening, and water filtration provided by mangroves.[64] Pacific seabirds that breed on low-lying atolls will lose large segments of their breeding populations[65] as their habitat is increasingly and more extensively covered by seawater.

Impacts to the built environment on low-lying portions of high islands, where nearly all airports are located and where each island's road network is sited,[66] will be nearly as profound as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. In Hawai'i, for example, where tourism comprises 26% of the state's economy, damage to tourism infrastructure could have large economic impacts –the loss of Waikīkī Beach alone could lead to an annual loss of $2 billion in visitor expenditures.[67]

Higher Sea Level Rise in Western Pacific

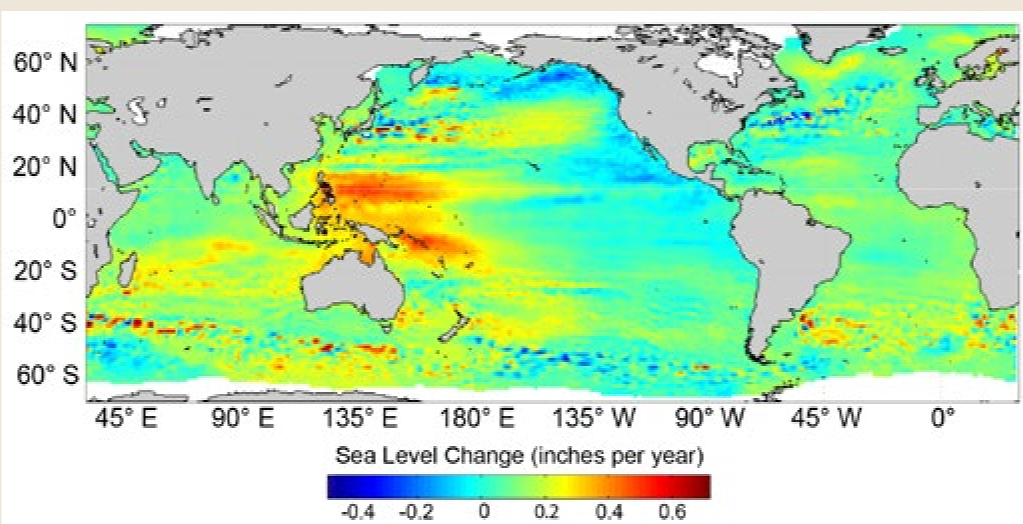

Figure 23.8. Map shows large variations across the Pacific Ocean in sea level trends for 1993-2010. The largest sea level increase has been observed in the western Pacific. (Figure source: adapted from Merrifield 2011[57] by permission of American Meteorological Society).

Key Message 5: Threats to Lives, Livelihoods, and Cultures

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

All of the climate change impacts described above will have an impact on human communities in Pacific Islands. Because Pacific Islands are almost entirely dependent upon imported food, fuel, and material, the vulnerability of ports and airports to extreme events, sea level rise, and increasing wave heights is of great concern. Climate change is expected to have serious effects on human health, for example by increasing the incidence of dengue fever (Ch. 9: Human Health).[68] In addition, sea level rise and flooding are expected to overwhelm sewer systems and threaten public sanitation.

The traditional lifestyles and cultures of indigenous communities in all Pacific Islands will be seriously affected by climate change (see also Chapter 12: Indigenous Peoples). Sea level rise and associated flooding is expected to destroy coastal artifacts and structures[69] or even the entire land base associated with cultural traditions.[70] Drought threatens traditional food sources such as taro and breadfruit, and coral death from warming-induced bleaching will threaten subsistence fisheries in island communities.[46] Climate change related environmental deterioration for communities at or near the coast, coupled with other socioeconomic or political motivations, is expected to lead individuals, families, or communities to consider moving to new locations. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Adaptation Activities

Adaptive capacity in the region varies and reflects the histories of governance, the economies, and the geographical features of the island/atoll site. High islands can better support larger populations and infrastructure, attract industry, foster institutional growth, and thus bolster adaptive capacity;[2] but these sites have larger policy or legal hurdles that complicate coastal planning.[71] Low islands have a different set of challenges. Climate change related migration, for example, is particularly relevant to the low island communities in the Republic of the Marshall Islands (RMI) and the Federated States of Micronesia (FSM), and presents significant practical, cultural, and legal challenges.[72]

In Hawai‘i, state agencies have drafted a framework for climate change adaptation by identifying sectors affected by climate change and outlining a process for coordinated statewide adaptation planning.[73] Both Hawai‘i and American Samoa specifically consider climate change in their U.S. Federal Emergency Management Agency (FEMA) hazard mitigation plans, and the Commonwealth of Northern Mariana Islands lists climate variability as a possible hazard related to extreme climate events.[74] The U.S. Pacific Island Freely Associated States (which includes the Republic of Palau, FSM, and RMI; Figure 23.1) have worked with regional organizations to develop plans and access international resources. Each of these jurisdictions has developed a status report on integrating climate-related hazard information in disaster risk reduction planning and has developed plans for adaptation to climate-related disaster risks.[75] Overall, there is very little research on the effectiveness of alternative adaptation strategies for Pacific Islands and their communities. The regional culture of communication and collaboration provides a strong foundation for adaptation planning and will be important for building resilience in the face of the changing climate.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was convening three focus area workshops as part of the Pacific Islands Regional Climate Assessment (PIRCA). The PIRCA is a collaborative effort aimed at assessing the state of climate knowledge, impacts, and adaptive capacity in Hawai‘i and the U.S. Affiliated Pacific Islands. These workshops included representatives from the U.S. federal agencies, universities, as well as international participants from other national agencies and regional organizations. The workshops led to the formulation of a foundational Technical Input Report (TIR).[2] The report consists of nearly 140 pages, with almost 300 references, and was organized into 5 chapters by 11 authors.

The chapter author team engaged in multiple technical discussions via regular teleconferences that permitted a careful review of the foundational TIR[2] and of approximately 23 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions included a face-to-face meeting held on July 9, 2012. These discussions were supported by targeted consultation among the lead and contributing authors of each message. There were several iterations of review and comment on draft key messages and associated content.

Key message #1 Traceable Account

Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.

Description of evidence base

The key message was chosen based on input from the extensive evidence documented in the Hawai‘i Technical Input Report[2] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Ocean warming: There is ample evidence that sea-surface temperatures have already risen throughout the region based on clear observational data, with improved data with the advent of satellite and in situ (ARGO & ship-based) data.[7] Assessment of the literature for the region by other governmental bodies (such as Australian Bureau of Meteorology [ABOM] and the Commonwealth Scientific and Industrial Research Organization [CSIRO]) point to continued increases under both B1 and A2 scenarios.[8]

Ocean acidification: Globally, the oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually, and becoming more acidic as a result (Ch. 2: Our Changing Climate, Key Message 12). Historical and current observations of aragonite saturation state (Ωar) for the Pacific Ocean show a decrease from approximately 4.9 to 4.8 in the Central North Pacific (Hawaiian Islands); in the Western North Pacific (Republic of Marshall Islands, Commonwealth of Northern Mariana Islands, Federated States of Micronesia, Republic of Palau, Guam), it has declined from approximately 4.5 to 3.9 in 2000, and to 4.1 in the Central South Pacific (American Samoa) (this chapter: Figure 23.3; Ch. 24: Oceans and Marine Resources).[19] Projections from CMIP3 models indicate the annual maximum aragonite saturation state will reach values below 3.5 by 2035 in the waters of the Republic of the Marshall Islands (RMI), by 2030 in the Federated States of Micronesia (FSM), by 2040 in Palau, and by 2060 around the Samoan archipelago. These values are projected to continue declining thereafter.[2] The recently published *Reefs at Risk Revisited*[25] estimates aragonite saturation state (as an indicator of ocean acidification) for CO_2 stabilization levels of 380 ppm, 450 ppm, and 500 ppm, which correspond approximately to the years 2005, 2030, and 2050 under the A1B emissions scenario (which assumes similar emissions to the A2 scenario through 2050 and a slow decline thereafter) (Figure 4.4 from Keener et al. 2012[2]).

Bleaching events: These have been well-documented in extensive literature worldwide due to increasing temperatures, with numerous studies in Hawai‘i and the Pacific Islands.[9,10]

Disease outbreaks: Reports of coral diseases have been proliferating in the past years,[11,13] but few have currently been adequately described, with causal organisms identified (for example, fulfill Koch's Postulates).

Reduced growth: There is abundant evidence from laboratory experiments that lower seawater pH reduces calcification rates in marine organisms (for example, Feely et al. 2009[19]). However, actual measurements on the effects of ocean acidification on coral reef ecosystems in situ or in complex mesocosms are just now becoming available, and these measurements show that there are large regional and diel variability in pH and pCO_2.[76] The role of diel and regional variability on coral reef ecosystems requires further investigation.

Distribution patterns of coastal and ocean fisheries: Evidence of the effects of ocean acidification on U.S. fisheries in Hawai'i and the Pacific Islands is currently limited (Lehodey et al. 2011)[28] but there is accumulating evidence for ecosystem impacts.

New information and remaining uncertainties

New information: Since the 2009 National Climate Assessment,[77] considerable effort has been employed to understand the impacts of ocean acidification (OA) on marine ecosystems, including recent ecosystem-based efforts.[22,28] Studies of OA impacts on organisms has advanced considerably, with careful chemistry using worldwide standard protocols making inroads into understanding a broadening range of organisms.

However, predicting the effect of ocean acidification on marine organisms and marine coral reef ecosystems remains the key issue of uncertainty. The role of community metabolism and calcification in the face of overall reduction in aragonite saturation state must be investigated.

Understanding interactions between rising temperatures and OA remains a challenge. For example, high temperatures simultaneously cause coral bleaching, as well as affect coral calcification rates, with both impacts projected to increase in the future.

Assessment of confidence based on evidence

There is **very high** confidence that ocean acidification and decreased aragonite saturation is taking place and is projected to continue. There is **high** confidence that ocean warming is taking place and is projected to continue; there is **medium** confidence that the thermal anomalies will lead to continued coral bleaching and coral disease outbreaks.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.

Description of evidence base

There is abundant and definitive evidence that air temperature has increased and is projected to continue to increase over the entire region,[8,41,78] as there is globally (Ch. 2: Our Changing Climate, Key Message 3).

In Hawai'i and the Central North Pacific (CNP), projected annual surface air temperature increases are 1.0°F to 2.5°F by 2035, relative to 1971-2000.[40,42] In the Western North Pacific (WNP), the projected increases are 2.0°F to 2.3°F by 2030, 6.1°F to 8.5°F by 2055, and 4.9°F to 9.2°F by 2090.[8] In the central South Pacific (CSP), projected annual surface air temperature increases are 1.1°F to 1.3°F by 2030, 1.8°F to 2.5°F by 2055, and 2.5°F to 4.9°F by 2090.[8] (Please note that the islands that comprise the U.S. Pacific Islands Region are shown in Figure 23.1).

In Hawai'i, mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high variability related to El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).[34,35] For the WNP, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region and slight upward trends in precipitation have been seen for the western-most islands, with high ENSO-related variability.[8] In American Samoa, no trends in average rainfall are apparent based on the very limited available data.[8,37]

For the region as a whole, models disagree about projected changes in precipitation. Mostly models predict increases in mean annual rainfall and suggest a slight dry season decrease and wet season increase in precipitation.[8] However, based on statistical downscaling, one study[39] projected a 5% to 10% reduction in precipitation for the wet season and a 5% increase in the dry season for Hawai'i by the end of this century.

On most islands, increased temperatures coupled with decreased rainfall and increased drought will reduce the amount of freshwater for drinking and crop irrigation.[43] Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources.[44] The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time (Key Message 4, this chapter; Ch. 2: Our Changing Climate, Key Message 10).[2]

New information and remaining uncertainties

Climate change impacts on freshwater resources in the Pacific Islands region will vary because of differing island size and height, which affect water storage capability and susceptibility to coastal inundation. The impacts will also vary because of natural phase variability (for example, ENSO and PDO) in precipitation and storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location.

Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.

Assessment of confidence based on evidence

Freshwater systems are inherently fragile in many Pacific Islands. Historical observations show strong evidence of a decreasing trend for rainfall in Hawai'i and many other Pacific Islands (Ch. 2: Our Changing Climate).[2] There is abundant and definitive evidence that air temperature has increased and will continue to increase. All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. Based on the evidence base and remaining uncertainties, we have **high** confidence in the key message.

Key message #3 Traceable Account

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Description of evidence base

In Hawai'i and the Central North Pacific (CNP), projected annual surface air temperature increases are 1.0°F to 2.5°F by 2035, relative to 1971-2000.[40,42] In the Western North Pacific (WNP), the projected increases are 2.0°F to 2.3°F by 2030, 6.1°F to 8.5°F by 2055, and 4.9°F to 9.2°F by 2090.[8] In the Central South Pacific (CSP), projected annual surface air temperature increases are 1.1°F to 1.3°F by 2030, 1.8°F to 2.5°F by 2055, and 2.5°F to 4.9°F by 2090.[8] In Hawai'i the rate of increase has been greater at high elevations.[41] (Please note that the islands that comprise the U.S. Pacific Islands Region are shown in Figure 23.1).

In Hawai'i mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high ENSO and PDO-related variability.[34,35,36] Projects based on statistical downscaling[39] suggest the most likely precipitation scenario for Hawai'i for the 21st century to be a 5% to 10% reduction for the wet season and a 5% increase in the dry season.

On high islands like Hawai'i, decreases in precipitation and baseflow[35] are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and on water-intensive sectors such as agriculture and tourism.

Hawaiian high-elevation alpine ecosystems on Hawai'i and Maui islands are already beginning to show strong signs of increased drought and warmer temperatures.[50] Demographic data for the Haleakalā silversword, a unique (endemic to upper Haleakalāvolcano) and integral component of the alpine ecosystem in Haleakalā National Park, Maui, have recorded a severe decline in plant numbers over the past two decades.[51] Many of Hawai'i's endemic forest birds, marvels of evolution largely limited to high-elevation forests by predation and disease, are increasingly vulnerable as rising temperatures allow the disease-vectoring mosquitoes to thrive upslope and thereby reduce the extent of safe bird habitat.[48,52]

New information and remaining uncertainties

Climate change impacts in the Pacific Islands region will vary because of differing island size and height. The impacts will also vary because of natural phase variability (for example, El Niño-Southern Oscillation and Pacific Decadal Oscillation) in precipitation and storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location.

Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.[2,8]

Climate change ecosystem response is poorly understood.[2]

Assessment of confidence based on evidence

Terrestrial and marine ecosystems are already being impacted by local stressors, such as coastal development, land-based sources of pollution, and invasive species.[2,25] There is abundant and definitive evidence that air temperature has increased and will continue to increase. Historical observations show strong evidence of a decreasing trend for rainfall in Hawai'i and many other Pacific Islands.[2] Given the evidence base and remaining uncertainties, confidence is **high** in this key message.

Key message #4 Traceable Account

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Description of evidence base

All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. Recent studies give higher sea level rise projections than those projected in 2007 by the Intergovernmental Panel on Climate Change[29] for the rest of this century (Ch. 2: Our Changing Climate, Key Message 10).[55]

Sea level is rising and is expected to continue to rise. Over the past few decades, global mean sea level, as measured by satellite altimetry, has been rising at an average rate of twice the estimated rate for the previous century, based on tide gauge measurements,[55] with models suggesting that global sea level will rise significantly over the course of this century. Regionally, the highest increases have been observed in the western tropical Pacific.[56] However, the current high rates of regional sea level rise in the western tropical Pacific are not expected to persist, as regional sea level will fall in response to a change in phase of natural variability.[62] Regional variations in sea level at interannual and interdecadal time scales are generally attributed to changes in prevailing wind patterns associated with El Niño-Southern Oscillation (ENSO) as well as the Pacific Decadal Oscillation (PDO) and low frequency components of the Southern Oscillation Index (SOI).[59]

For the region, extreme sea level events generally occur when high tides combine with some non-tidal residual change in water level. In the major typhoon zones (Guam and Commonwealth of the Northern Mariana Islands), storm-driven surges can cause coastal flooding and erosion regardless of tidal state. Wave-driven inundation events are a major concern for all islands in the region. At present, trends in extreme levels tend to follow trends in mean sea level.

Increasing mean water levels and the possibility of more frequent extreme water level events, and their manifestation as flooding and erosion, will threaten coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location, depending on how natural sea level variability combines with modest increases of mean levels.[62]

On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable.[62] Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and episodic inundation increases salinity of groundwater resources. Impacts to the built environment on low-lying portions of high islands will be much the same as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. One report stated: "Our analyses estimate that nearly $2.0 billion in overall visitor expenditures could be lost annually due to a complete erosion of Waikīkī Beach."[67]

Coastal and nearshore environments (sandy beaches, shallow coral reefs, seagrass beds, intertidal flats, and mangrove forests) and the vegetation and terrestrial animals in these systems will progressively be affected as sea level rise and high wave events alter atoll island size and shape and reduce habitat features necessary for survival. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10%–20% of total regional mangrove area over the next century.[63] Further, atoll-breeding Pacific seabirds will lose large segments of their breeding populations[65] as their habitat is increasingly and more extensively inundated.

Major uncertainties

Sea levels in the Pacific Ocean will continue to rise with global sea level. Models provide a range of predictions, with some suggesting that global warming may raise global sea level considerably over the course of this century. The range of predictions is large due in part to unresolved physical understanding of various processes, notably ice sheet dynamics.

Changes in prevailing wind patterns associated with natural climate cycles such as ENSO and the PDO affect regional variations in sea level at interannual and interdecadal time scales. Sea level at specific locales will continue to respond to changes in phase of these natural climate cycles. The current high rates of regional sea level rise in the western tropical Pacific are not expected to persist over time, falling once the trade winds begin to weaken.

Future wind wave conditions are difficult to project with confidence given the uncertainties regarding future storm conditions.

Assessment of confidence based on evidence

Evidence for global sea level rise is strong (Ch. 25: Coasts; Ch. 2: Our Changing Climate). Confidence is therefore **very high**. Modeling studies have yielded conflicting results as to how ENSO and other climate modes will vary in the future. As a result, there is **low** confidence in the prediction of future climate states and their subsequent influence on regional sea level.[62] Recent assessments of future extreme conditions generally place **low** confidence on region-specific projections of future storminess.[61]

For aspects of the key message concerning impacts, confidence is **high**.

Key message #5 Traceable Account

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

Description of evidence base

Climate change threatens communities, cultures, and ecosystems of the Pacific Islands both directly through impact on food and water security, for example, as well as indirectly through impacts on economic sectors including fisheries and tourism.

On most islands, increased temperatures, coupled with decreased rainfall and increased drought, will lead to an additional need for freshwater resources for drinking and crop irrigation.[43] This is particularly important for locations in the tropics and subtropics where observed data and model projections suggest that, by the end of this century, the average growing season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006. Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources.[44] The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time. These are but part of a cascade of impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities.[47] On high islands like Hawai'i, decreases in precipitation and baseflow[35] are already indicating that there will be impacts on freshwater ecosystems and aquatic species and on water-intensive sectors such as agriculture and tourism.

Increasing mean oceanic and coastal water levels and the possibility of more frequent extreme water level events with flooding and erosion will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location depending on how natural sea level variability combines with modest increases of mean levels.[62] On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and episodic inundation increases salinity of groundwater resources.

With respect to cultural resources, impacts will extend from the loss of tangible artifacts and structures[69] to the intangible loss of a land base and the cultural traditions that are associated with it.[70]

New information and remaining uncertainties

Whenever appraising threats to human society, it is uncertain the degree to which societies will successfully adapt to limit impact. For island communities, though, the ability to migrate is very limited, and the ability to adapt is especially limited. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Assessment of confidence based on evidence

Evidence for climate change and impacts is strong, but highly variable from location to location. One can be highly confident that climate change will continue to pose varied threats in the region. Adaptive capacity is also highly variable among the islands, so the resulting situation will play out differently in different places. Confidence is therefore **medium**.

Climate Change Impacts in the United States

CHAPTER 24
OCEANS AND MARINE RESOURCES

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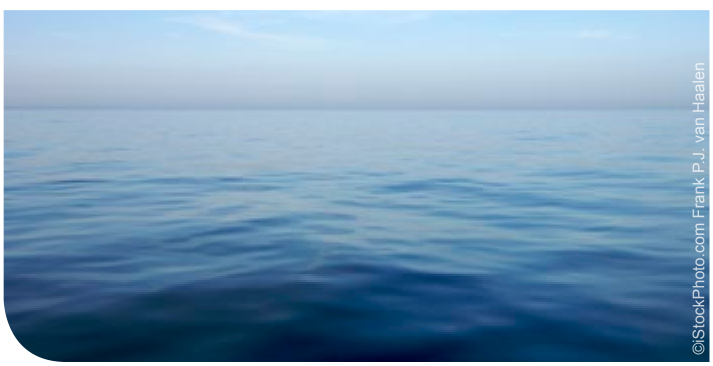
24 OCEANS AND MARINE RESOURCES

Key Messages

1. **The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.**
2. **The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.**
3. **Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.**
4. **Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and marine life, including corals, abalones, oysters, fishes, and marine mammals.**
5. **Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.**
6. **In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.**

As a nation, we depend on the oceans for seafood, recreation and tourism, cultural heritage, transportation of goods, and, increasingly, energy and other critical resources. The U.S. Exclusive Economic Zone extends 200 nautical miles seaward from the coasts, spanning an area about 1.7 times the land area of the continental U.S. and encompassing waters along the U.S. East, West, and Gulf coasts, around Alaska and Hawai'i, and including the U.S. territories in the Pacific and Caribbean. This vast region is host to a rich diversity of marine plants and animals and a wide range of ecosystems, from tropical coral reefs to Arctic waters covered with sea ice.



Oceans support vibrant economies and coastal communities with numerous businesses and jobs. More than 160 million people live in the coastal watershed counties of the United States, and population in this zone is expected to grow in the future. The oceans help regulate climate, absorb carbon dioxide (an important greenhouse, or heat-trapping, gas), and strongly influence weather patterns far into the continental interior. Ocean issues touch all of us in both direct and indirect ways.[1,2,3]

Changing climate conditions are already affecting these valuable marine ecosystems and the array of resources and services we derive from the sea. Some climate trends, such as rising seawater temperatures and ocean acidification, are common across much of the coastal areas and open ocean worldwide. The biological responses to climate change often vary from region to region, depending on the different combinations of species, habitats, and other attributes of local systems. Data records for the ocean are often shorter and less complete than those on land, and for many biological variables it is still difficult to discern long-term ocean trends from natural variability.[4]

Key Message 1: Rising Ocean Temperatures

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Cores from corals, ocean sediments, ice records, and other indirect temperature measurements indicate the recent rapid increase of ocean temperature is the greatest that has occurred in at least the past millennium and can only be reproduced by climate models with the inclusion of human-caused sources of heat-trapping gas emissions.[5,6] The ocean is a critical reservoir for heat within Earth's climate system, and because of seawater's large heat storing capacity, small changes in ocean temperature reflect large changes in ocean heat storage. Direct measurements of ocean temperatures show warming beginning in about 1970 down to at least 2,300 feet, with stronger warming near the surface leading to increased thermal stratification (or layering) of the water column.[7,8] Sea surface temperatures in the North Atlantic and Pacific, including near U.S. coasts, have also increased since 1900.[9,10] In conjunction with a warming climate, the extent and thickness of Arctic sea ice has decreased rapidly over the past four decades.[11,12] Models that best match historical trends project seasonally ice-free northern waters by the 2030s.[13]

Climate-driven warming reduces vertical mixing of ocean water that brings nutrients up from deeper water, leading to potential impacts on biological productivity. Warming and altered ocean circulation are also expected to reduce the supply of oxygen to deeper waters, leading to future expansion of sub-surface low-oxygen zones.[15] Both reduced nutrients at the surface and reduced oxygen at depth have the potential to change ocean productivity.[14] Satellite observations indicate that warming of the upper ocean on year-to-year timescales leads to reductions in the biological productivity of tropical and subtropical (the region just outside the tropics) oceans and expansion of the area of surface waters with very low quantities of phytoplankton (microscopic marine plants) biomass.[16] Ecosystem models suggest that the same patterns of productivity change will occur over the next century as a consequence of warming during this century, perhaps also with increasing productivity near the poles.[17] These changes can affect ecosystems at multiple levels of the food web, with consequent changes for fisheries and other important human activities that depend on ocean productivity.[4,18]

Other changes in the physical and chemical properties of the ocean are also underway due to climate change. These include rising sea level,[19] changes in upper ocean salinity (including reduced salinity of Arctic surface waters) resulting from altered inputs of freshwater and losses from evaporation, changes in wave height from changes in wind speed, and changes in oxygen content at various depths – changes that will affect marine ecosystems and human uses of the ocean in the coming years.[4]

Observed Ocean Warming

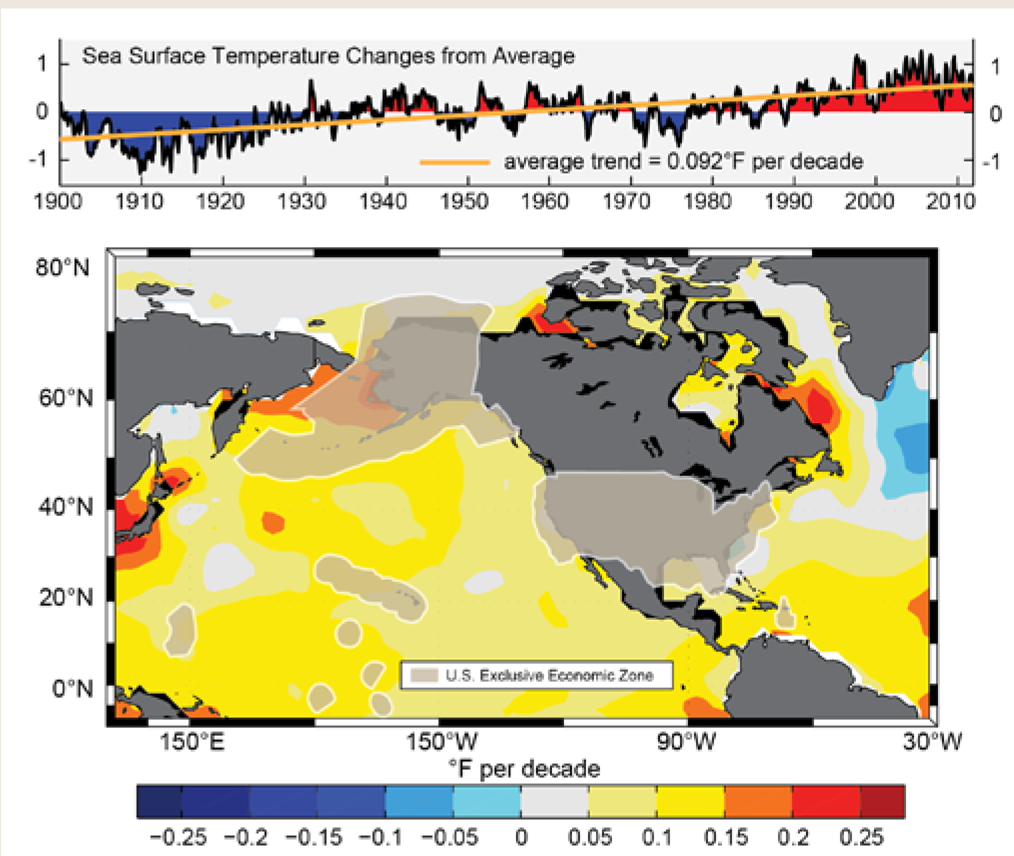


Figure 24.1. Sea surface temperatures for the ocean surrounding the U.S. and its territories have warmed by more than 0.9°F over the past century (top panel). There is significant variation from place to place, with the ocean off the coast of Alaska, for example, warming far more rapidly than other areas (bottom panel). The gray shading on the map denotes U.S. land territory and the regions where the U.S. has rights over the exploration and use of marine resources, as defined by the U.S. Exclusive Economic Zone (EEZ). (Figure source: adapted from Chavez et al. 2011[14]).

While the long-term global pattern is clear, there is considerable variability in the effects of climate change regionally and locally because oceanographic conditions are not uniform and are strongly influenced by natural climate fluctuations. Trends during short periods of a decade or so can be dominated by natural variability.[25] For example, the high incidence of La Niña events in the last 15 years has played a role in the observed temperature trends.[26]

Analyses[27] suggest that more of the increase in heat energy during this period has been transferred to the deep ocean (see also Ch. 2: Our Changing Climate). While this might temporarily slow the rate of increase in surface air temperature, ultimately it will prolong the effects of global warming because the oceans hold heat for longer than the atmosphere does.

Interactions with processes in the atmosphere and on land, such as rainfall patterns and runoff, also vary by region and are strongly influenced by natural climate fluctuations, resulting in additional local variation in the observed effects in the ocean.

Marine ecosystems are also affected by other human-caused local and regional disturbances such as overfishing, coastal habitat loss, and pollution, and climate change impacts may exacerbate the effects of these other human factors.

Ocean Impacts of Increased Atmospheric Carbon Dioxide

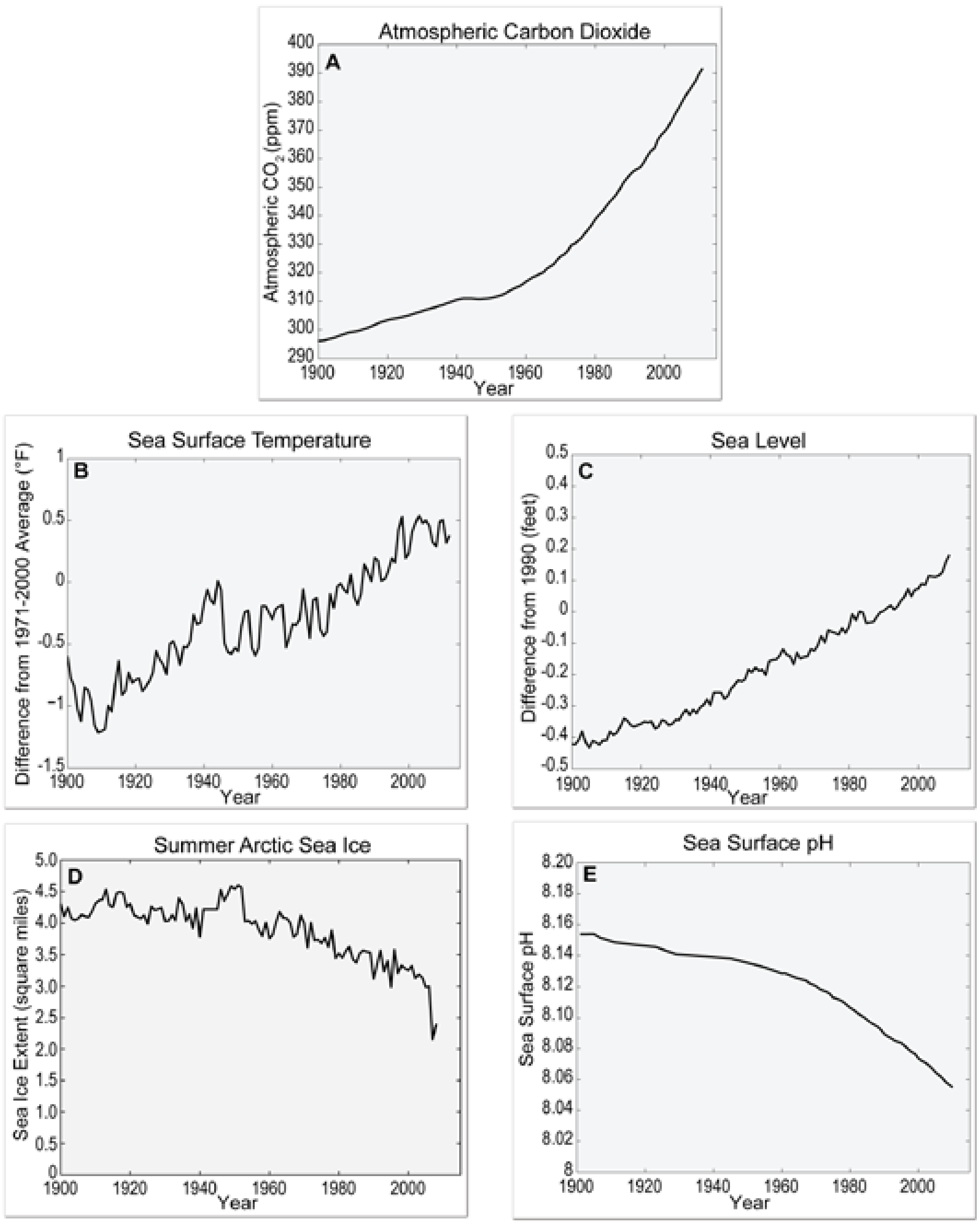


Figure 24.2. As heat-trapping gases, primarily *carbon dioxide (CO_2)* (panel A), have increased over the past decades, not only has air temperature increased worldwide, but so has the temperature of the ocean's surface (panel B). The increased ocean temperature, combined with melting of glaciers and ice sheets on land, is leading to higher sea levels (panel C). Increased air and ocean temperatures are also causing the continued, dramatic decline in Arctic sea ice during the summer (panel D). Additionally, the ocean is becoming more acidic as increased atmospheric *CO_2* dissolves into it (panel E). (CO_2 data from Etheridge 2010,[20] Tans and Keeling 2012,[21] and NOAA NCDC 2012;[22] SST data from NOAA NCDC 2012[22] and Smith et al. 2008;[10] Sea level data from CSIRO 2012[23] and Church and White 2011;[19] Sea ice data from University of Illinois 2012;[24] pH data from Doney et al. 2012[4]).