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

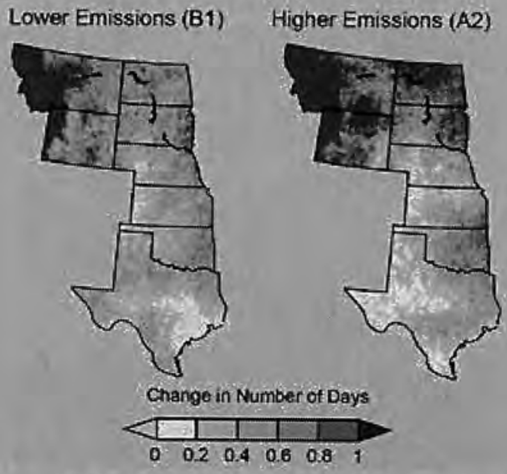

Figure 19.4. The number of days with the heaviest precipitation is not projected to change dramatically. By mid-century (2041-2070), the projected change in days exceeding those precipitation amounts remains greatest in the northern area for both the lower emissions scenario (B1) and for the higher emissions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

Projected Change in Number of Consecutive Dry Days

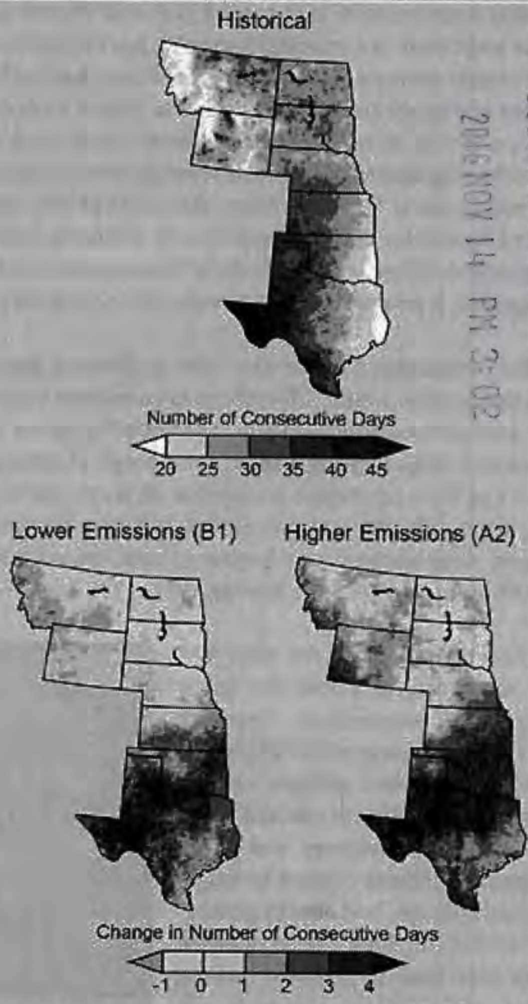

Figure 19.5. Current regional trends of a drier south and a wetter north are projected to become more pronounced by mid-century (2041-2070 as compared to 1971-2000 averages). Maps show the maximum annual number of consecutive days in which limited (less than 0.01 inches) precipitation was recorded on 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

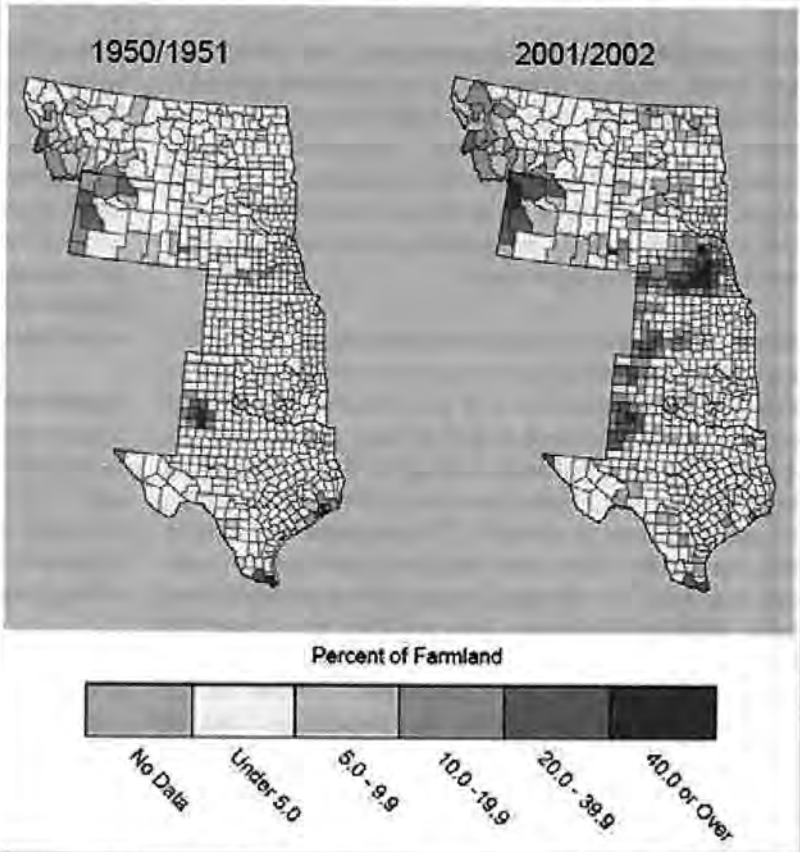

Figure 19.6. Irrigation in western Kansas, Oklahoma, and Texas supports crop development in semiarid areas. Declining aquifer levels threaten the ability to maintain production. Some aquifer-dependent regions, like southeastern Nebraska, have seen steep rises in irrigated farmland, from around 5% to 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]

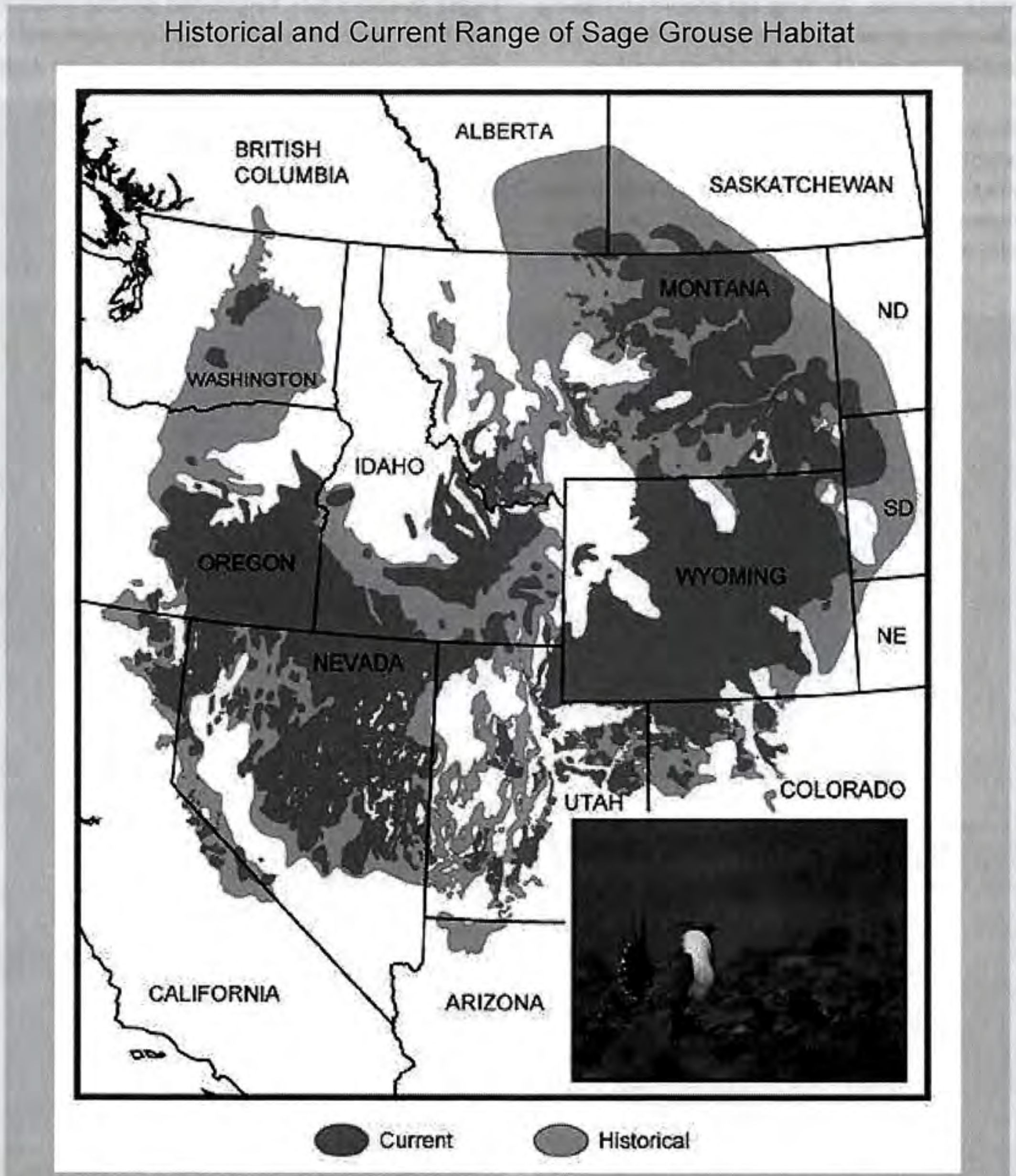

Figure 19.7. Comparing estimates of Greater Sage Grouse distribution from before settlement of the area (light green: prior to about 1800) with the current range (dark green: 2000) shows fragmentation of the sagebrush habitat required by this species. Over the last century, the sagebrush ecosystem has 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-

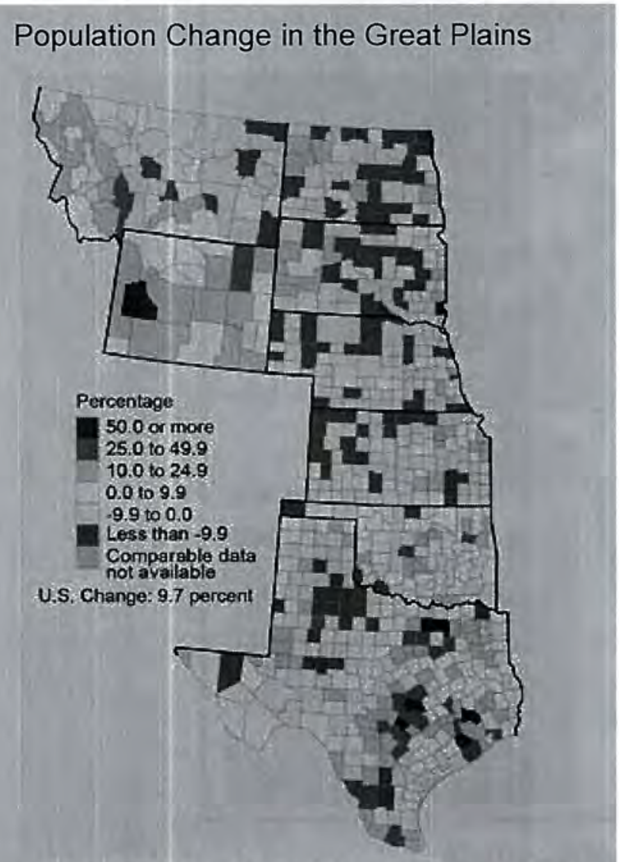

Figure 19.8. Demographic shifts continue to reshape communities in the Great Plains, with many central Great Plains communities losing residents. Rural and tribal communities will face additional challenges in dealing with climate change impacts due to demographic changes in the region (Ch. 14: Rural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

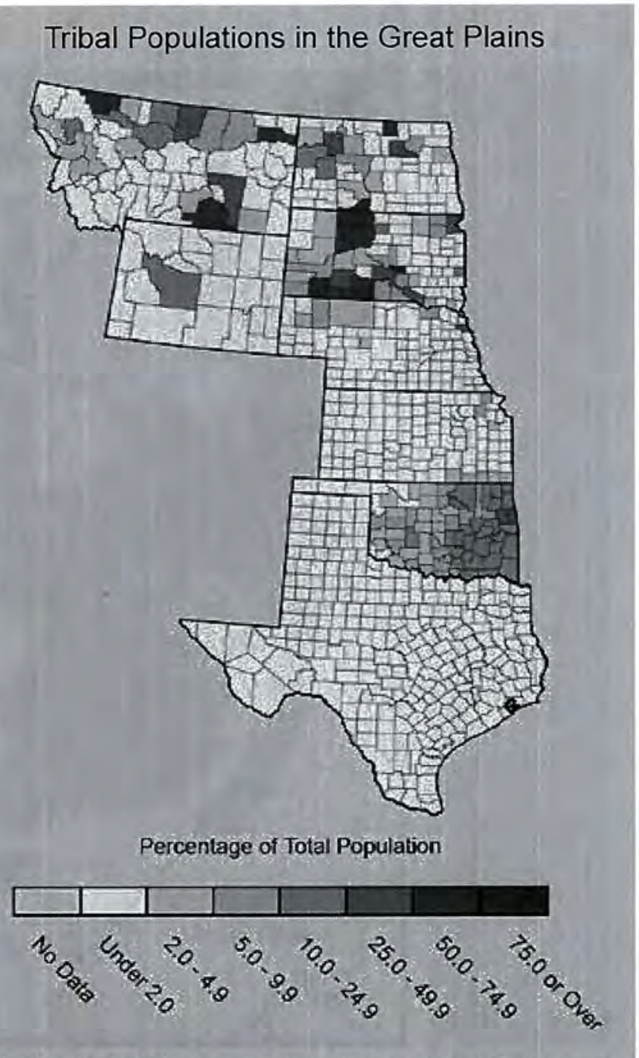

Figure 19.9. Tribal populations in the Great Plains are concentrated near large reservations, like various Sioux tribes in South Dakota and Blackfeet and Crow reservations in Montana; and in Cherokee, Chickasaw, Choctaw, and other tribal lands in Oklahoma (Figure source: reproduced from Atlas of the 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 100°F. 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).

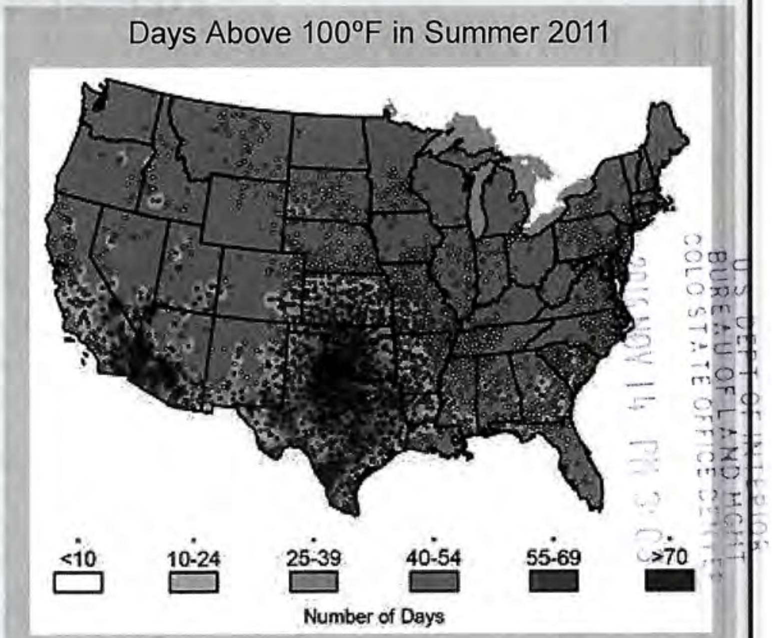

Figure 19.10. In 2011, cities including Houston, Dallas, Austin, Oklahoma City, and Wichita, among others, all set records for the highest number of days recording temperatures of 100°F or higher in those cities' recorded history. The black circles denote the location of observing stations recording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

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

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Increases in heavy downpours contribute to flooding.

19: GREAT PLAINS

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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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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

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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.

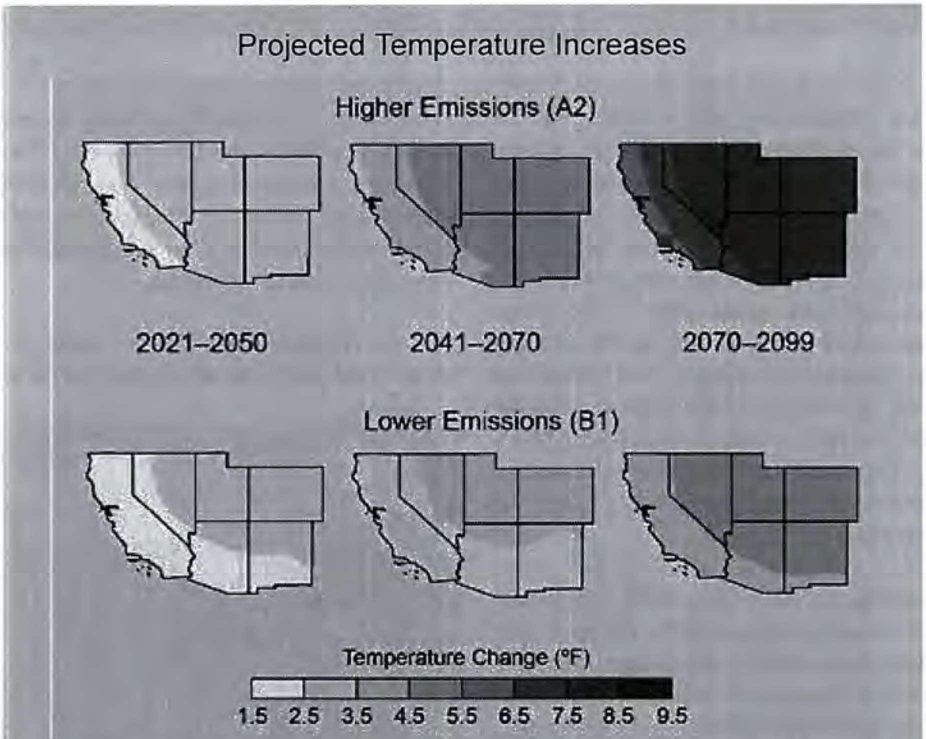

Figure 20.1. Maps show projected changes in average, as compared to 1971-1999. Top row shows projections assuming heat-trapping gas emissions continue to rise (A2). Bottom row shows projections assuming substantial reductions in emissions (B1). (Figure source: adapted from Kunkel et al. 2013[17]).

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

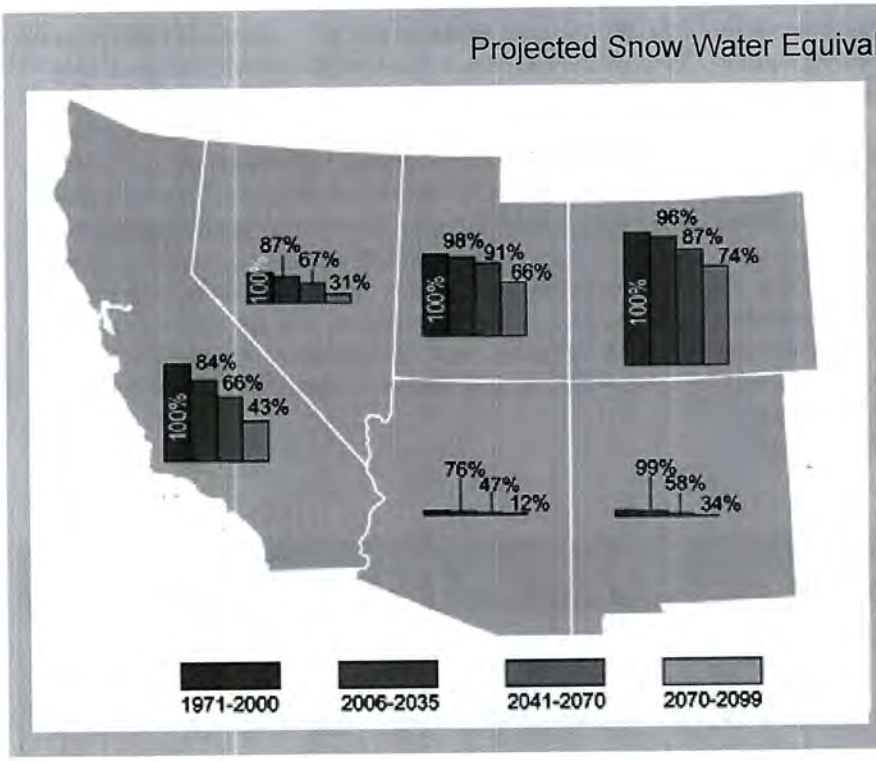

Figure 20.2. Snow water equivalent (SWE) refers to the amount of water held in a volume of snow, which depends on the density of the snow and other factors. Figure shows projected snow water equivalent for the Southwest, as a percentage of 1971-2000, assuming continued increases in global emissions (A2 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]


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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

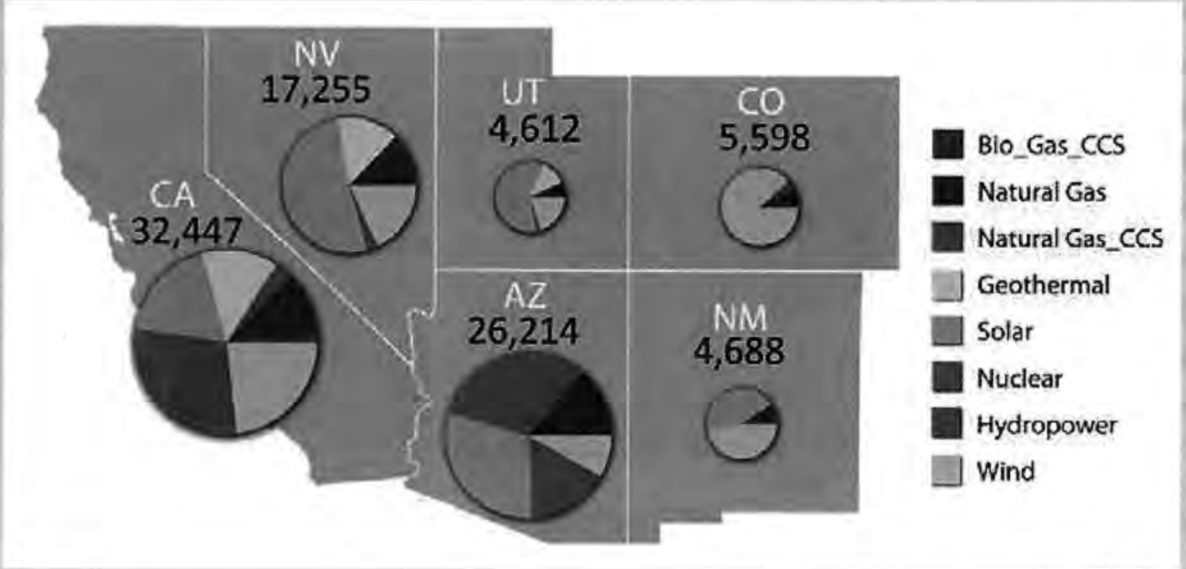

Figure 20.3. Major shifts in how electricity is produced can lead to large reductions in heat-trapping gas emissions. Shown is an illustrative scenario in which different energy combinations could, by 2050, achieve an 80% reduction of heat-trapping gas emissions from 1990 levels in the electricity sector 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

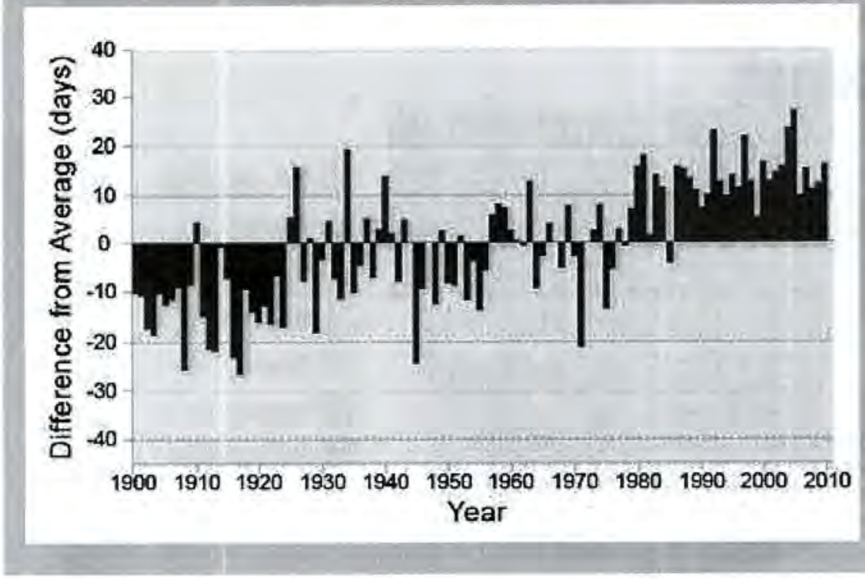

Figure 20.4. The frost-free season is defined as the period between the last occurrence of 32°F in spring and the first occurrence of 32°F in the subsequent fall. The chart shows significant increases in the number of consecutive frost-free days per year in the past three decades compared to the 1901-2010 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.


© AP Photo/The Press-Enterprise, Terry Pierson

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


1 February 2011: 16:51

20 January 2011: 11:32

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]

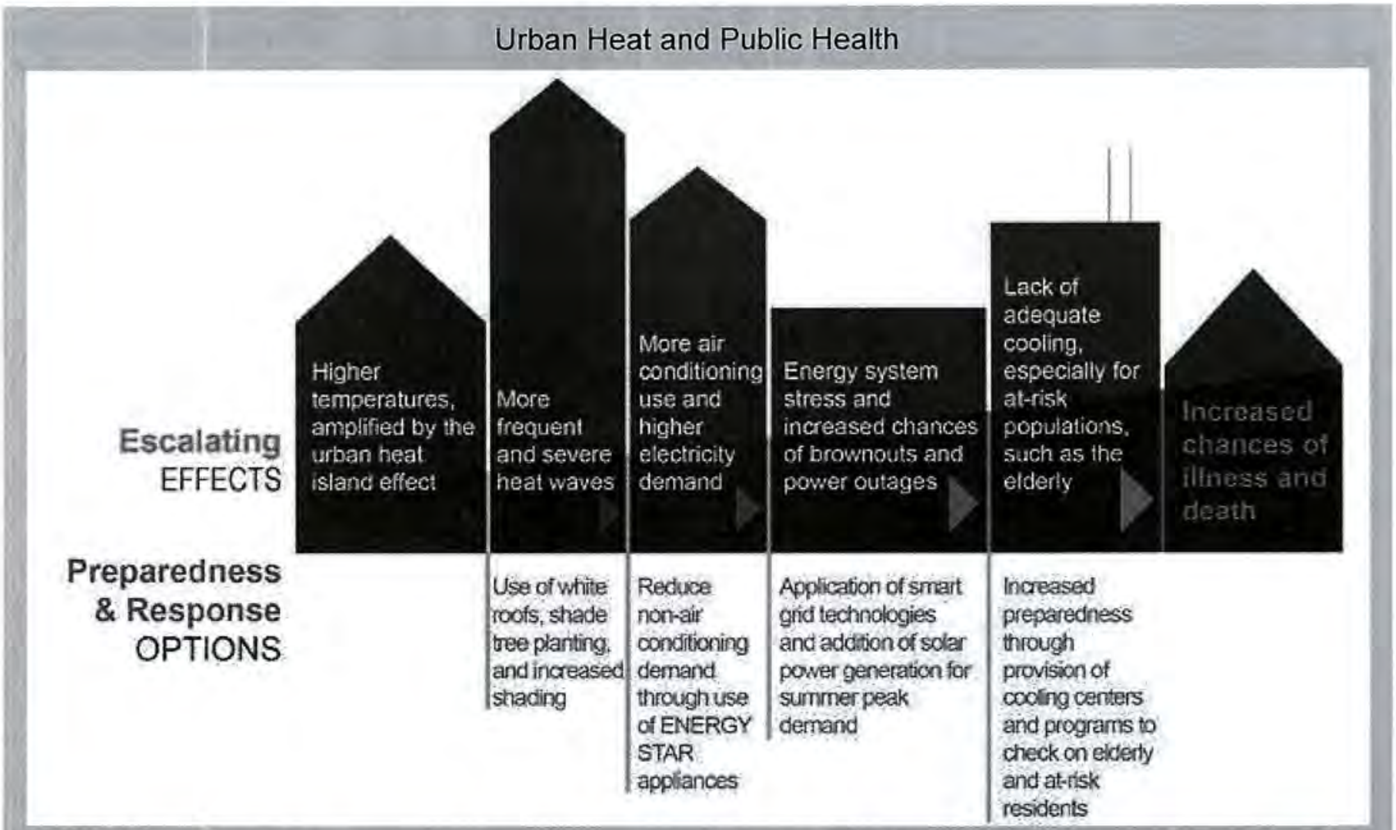

Figure 20.6. The projected increase in heat waves in Southwest cities (Ch. 2: Our Changing Climate, Key Message 7) increases the chances that a chain of escalating effects could lead to serious increases in illness and death due to heat stress. The top of the figure provides some of the links in that 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]

20: SOUTHWEST

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20: SOUTHWEST

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, nongovernmental 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.

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.

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 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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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]

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 pro-


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jected 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

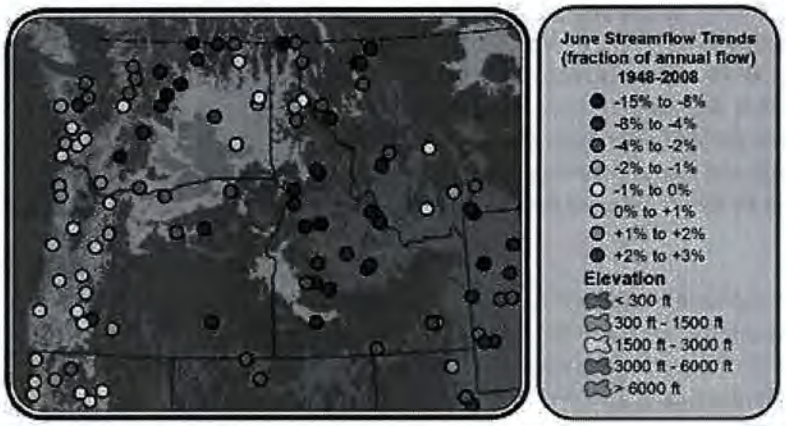

Figure 21.1. Reduced June flows in many Northwest snow-fed rivers is a signature of warming in basins that have a significant snowmelt contribution. The fraction of annual flow occurring in June increased slightly in rain-dominated coastal basins and decreased in mixed rain-snow basins and snowmelt-dominated 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

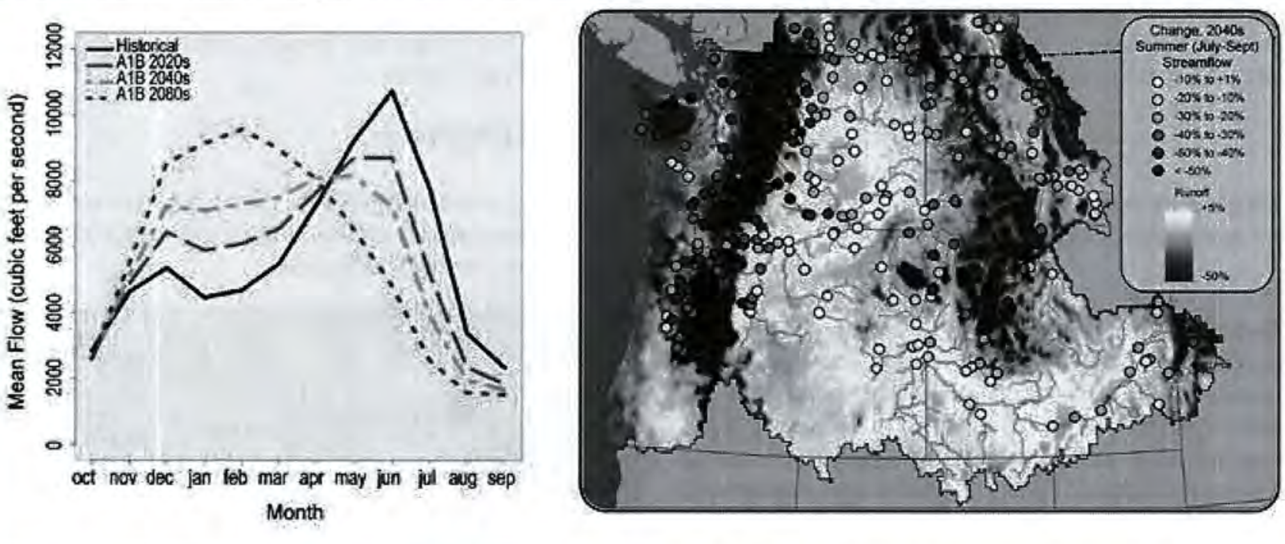

Figure 21.2. (Left) Projected increased winter flows and decreased summer flows in many Northwest rivers will cause widespread impacts. Mixed rain-snow watersheds, such as the Yakima River basin, an important agricultural area in eastern Washington, will see increased winter flows, earlier spring peak 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]


NOAA

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]


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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.


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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

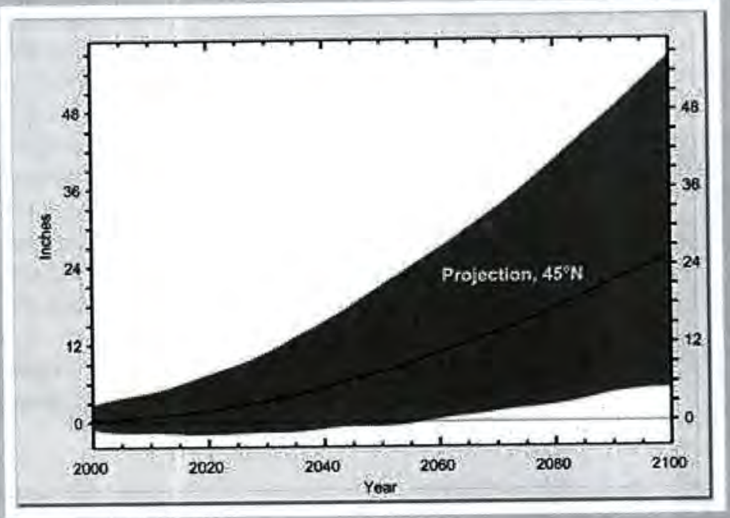

Figure 21.3. Projected relative sea level rise for the latitude of Newport, Oregon (relative to the year 2000) is based on a broader suite of emissions scenarios (ranging from B1 to A1FI) and a more detailed and regionally-focused calculation than those generally used in this assessment (see Ch. 2: Our 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

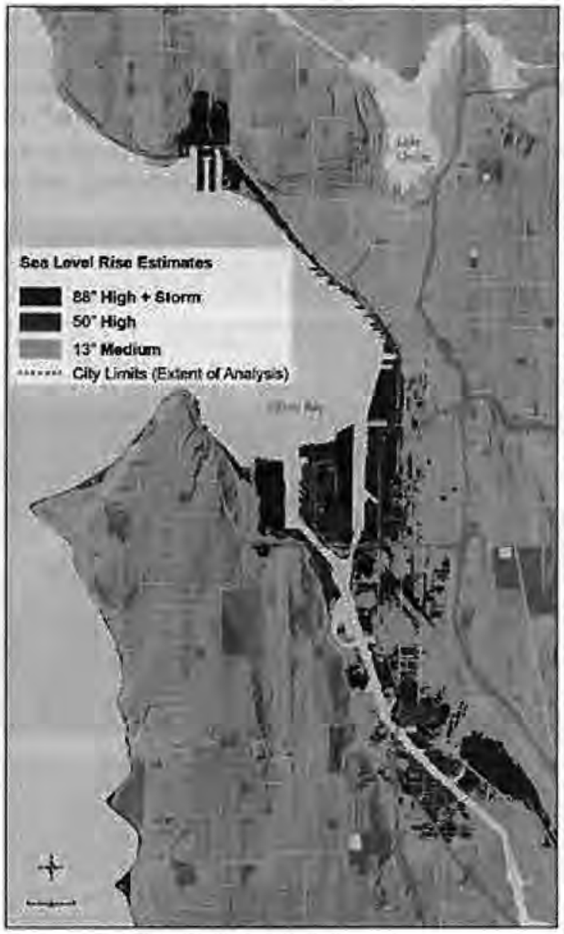

Figure 21.4. Areas of Seattle projected by Seattle Public Utilities to be below sea level during high tide (Mean Higher High Water) and therefore at risk of flooding or inundation are shaded in blue under three levels of sea level rise,[78] assuming no adaptation. (High [50 inches] and medium [13 inches] 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).

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).

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]

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

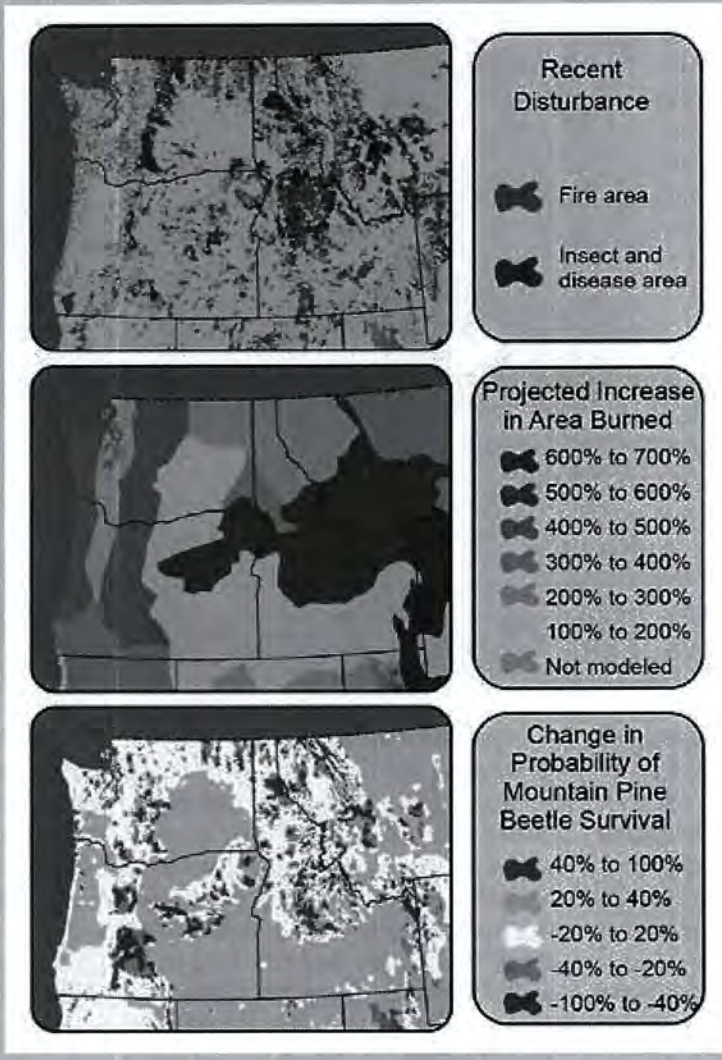

Figure 21.7.

(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 20th 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 20th 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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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]

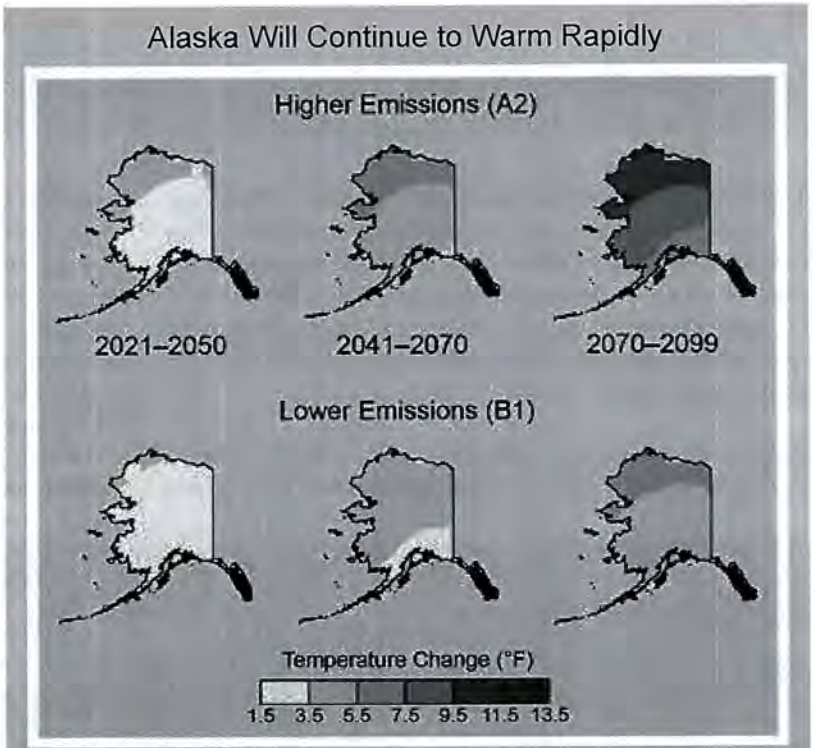

Figure 22.1. Northern latitudes are warming faster than more temperate regions, and Alaska has already warmed much faster than the rest of the country. Maps show changes in temperature, relative to 1971-1999, projected for Alaska in the early, middle, and late parts of this century, if heat-trapping 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.

Declining Sea Ice Extent

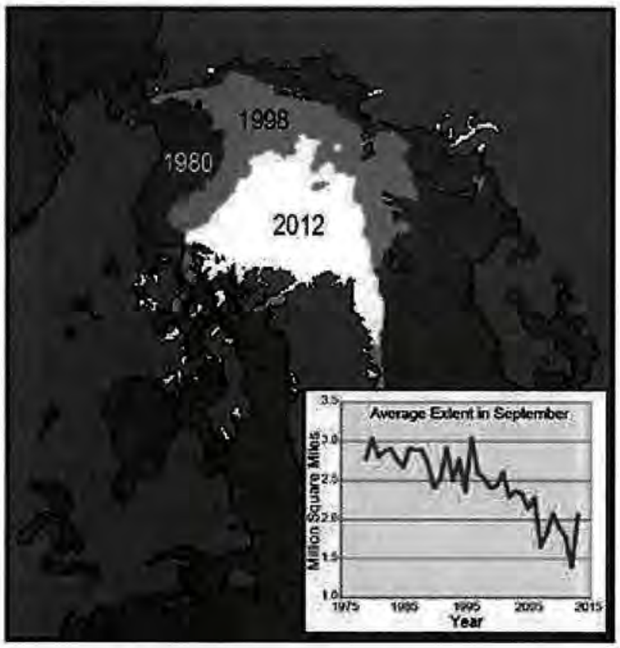

Figure 22.2. Average September extent of Arctic sea ice in 1980 (second year of satellite record and year of greatest September sea ice extent; outer red boundary), 1998 (about halfway through the time series; outer pink boundary) and 2012 (recent year of record and year of least September sea ice extent; 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]).

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

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 recordkeeping 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-

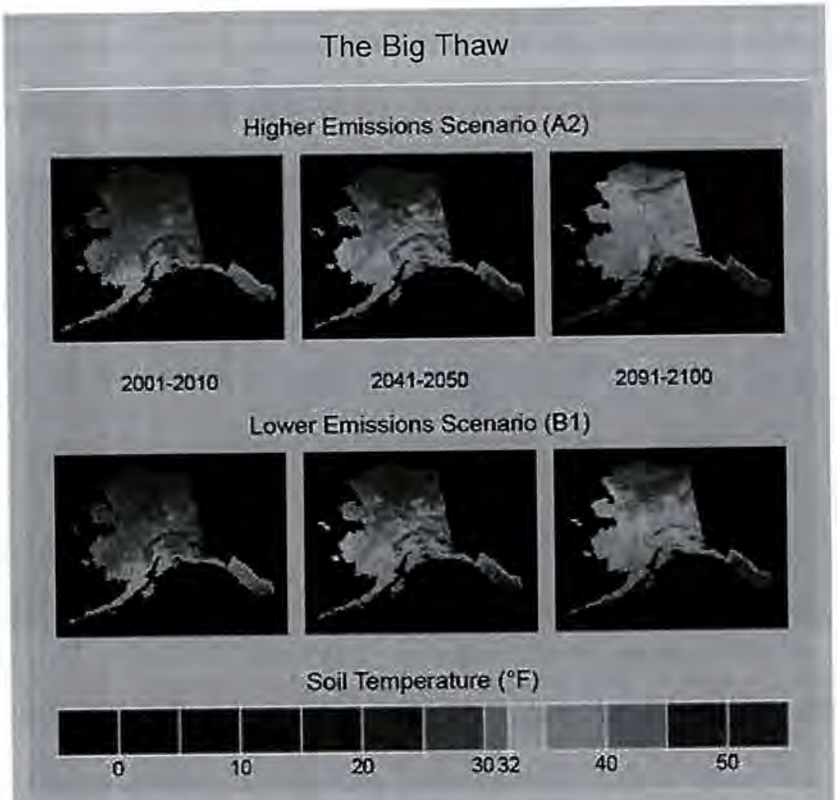

Figure 22.5. Projections for average annual ground temperature at a depth of 3.3 feet over time if emissions of heat-trapping gases continue to grow (higher emissions scenario, A2), and if they are substantially reduced (lower emissions scenario, B1). Blue shades represent areas below freezing at a depth 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]

Mounting Expenses from Permafrost Thawing

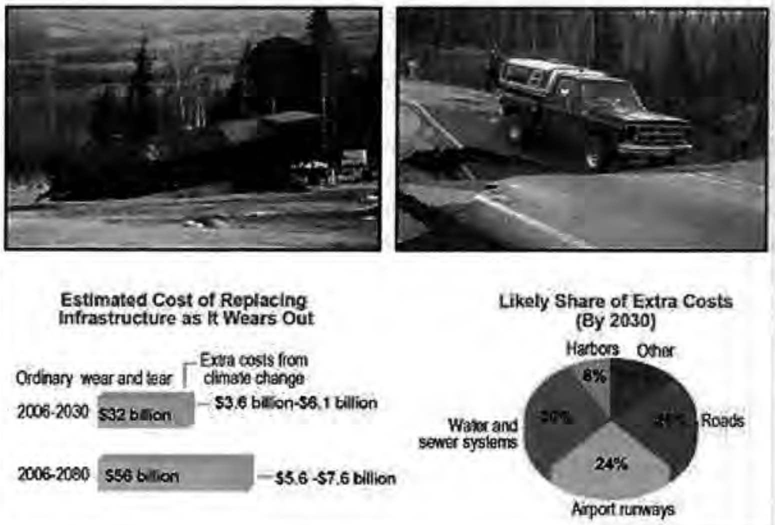

Figure 22.6. Effects of permafrost thaw on houses in interior Alaska (2001, top left), roads in eastern Alaska (1982, top right), and the estimated costs (with and without climate change) of replacing public infrastructure in Alaska, assuming a mid-range emissions scenario (A1B, with some decrease from 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).

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]

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.

Climate Change Impacts in the United States

CHAPTER 23

HAWAIʻI

AND U.S. AFFILIATED PACIFIC ISLANDS

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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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