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Recommended Citation for Chapter

Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. Huntington, J. Littell, M. McCammon, R. Thoman, and S. Trainor, 2018: Alaska. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 1185–1241. doi: 10.7930/NCA4.2018.CH26

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

26 Alaska

Anchorage, Alaska

Key Message 1

Marine Ecosystems

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

Key Message 2

Terrestrial Processes

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

Key Message 3

Human Health

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

Key Message 4

Indigenous Peoples

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

Key Message 5

Economic Costs

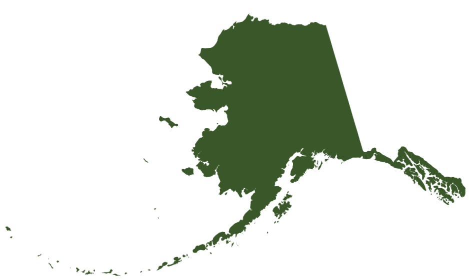
Climate warming is causing damage to infrastructure that will be costly to repair or replace, especially in remote Alaska. It is also reducing heating costs throughout the state. These effects are very likely to grow with continued warming. Timely repair and maintenance of infrastructure can reduce the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

Key Message 6

Adaptation

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

Executive Summary



Alaska is the largest state in the Nation, almost one-fifth the size of the combined lower 48 United States, and is rich in natural capital resources. Alaska is often identified as being on the front lines of climate change since it is warming faster than any other state and faces a myriad of issues associated with a changing climate. The cost of infrastructure damage from a warming climate is projected to be very large, potentially ranging from $110 to $270 million per year, assuming timely repair and maintenance. Although climate change does and will continue to dramatically transform the climate and environment of the Arctic, proactive adaptation in Alaska has the potential to reduce costs associated with these impacts. This includes the dissemination of several tools, such as guidebooks to support adaptation planning, some of which focus on Indigenous communities. While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

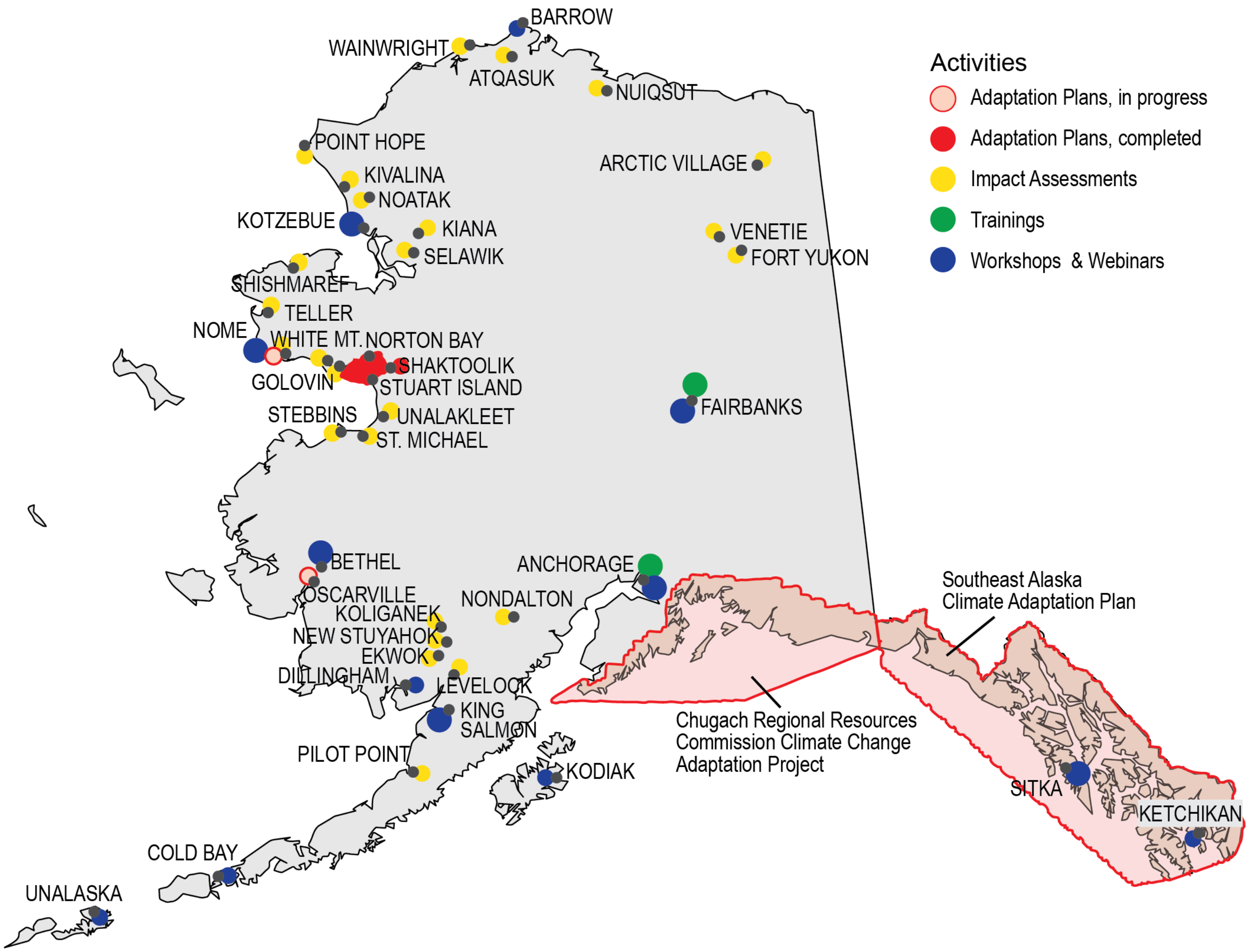
As the climate continues to warm, there is likely to be a nearly sea ice-free Arctic during the summer by mid-century. Ocean acidification is an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions and negatively affects organisms. Climate change will likely affect management actions and economic drivers, including fisheries, in complex ways. The use of multiple alternative models to appropriately characterize uncertainty in future fisheries biomass trajectories and harvests could help manage these challenges. As temperature and precipitation increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost is expected to continue, with associated impacts to infrastructure, river and stream discharge, water quality, and fish and wildlife habitat.

Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat in the future and in some cases requiring entire communities or portions of communities to relocate to safer terrain. The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States. Climate change exerts indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting disease ecology and food security, especially in rural communities. Alaska's rural communities are predominantly inhabited by Indigenous peoples who may be disproportionately vulnerable to socioeconomic and environmental change; however, they also have rich cultural traditions of resilience and adaptation. The impacts of climate change will likely affect all aspects of Alaska Native societies, from nutrition, infrastructure, economics, and health consequences to language, education, and the communities themselves.

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

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

Adaptation Planning in Alaska



The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;[4] the University of Alaska for invasive species;[5] and the Alaska Native Tribal Health Consortium for local observations of environmental change.[6] Additional examples of community-based monitoring can be found through the website of the Alaska Ocean Observing System.[7] *From Figure 26.9 (Source: adapted from Meeker and Kettle 2017[8]).*

Background

Alaska is the largest state in the Nation, spanning a land area of around 580,000 square miles, almost one-fifth the size of the combined lower 48 United States. Its geographic location makes the United States one of eight Arctic nations. The State has an abundance of natural resources and is highly dependent on oil, mining, fishing, and tourism revenues. Changes in climate can have positive and negative impacts on these resources.[9,10,11]

As part of the Arctic, Alaska is on the front lines of climate change[12,13] and is among the fastest warming regions on Earth (Ch. 2: Climate, KM 7).[14] It is warming faster than any other state, and it faces a myriad of issues associated with a changing climate. The retreat of arctic sea ice affects many Alaskans in different ways, such as through changes in fish and wildlife habitat that are important for subsistence, tourism, and recreational activities.[15,16] The warming of North Pacific waters can contribute to the northward expansion of marine fish species, ecosystem changes, and potential relocation of fisheries.[17] An ice-free Arctic also contributes to increases in ocean acidification (through greater ocean–atmosphere interaction), affecting marine mammal habitat and the growth and survival of fish and crab species that are important for both personal and commercial use.[18] Lack of sea ice also contributes to increased storm surge and coastal flooding and erosion, leading to the loss of shorelines and causing some communities to relocate.[19]

Thawing permafrost, melting glaciers, and the associated effects on Alaska's infrastructure and hydrology are also of concern to Alaskans. Thawing permafrost has negatively affected important infrastructure, which is costly to repair, and these costs are projected to increase.[20,21] Melting glaciers may affect hydroelectric power generation through changes in river discharge and associated changes in reservoir capacity.[22] A warming climate is also likely to increase the frequency and size of wildfires, potentially changing the type and extent of wildlife habitat favorable for some important subsistence species.[23,24,25] Climate change also brings a wide range of human health threats to Alaskans due to increased injuries, smoke inhalation, damage to vital infrastructure, decreased food and water security, and new infectious diseases.[10] The subsistence activities of local residents are also affected, which in turn affects food security, culture, and health.[26,27,28,29]

The cost of a warming climate is projected to be huge, potentially ranging from $3 to $6 billion, between 2008 and 2030 (in 2008 dollars; $3.3–$6.7 billion in 2015 dollars). There are, however, a number of opportunities for Alaskans to respond to these climate-related challenges, including several tools and guidebooks available to support adaptation planning, with some focused specifically on Indigenous communities.[30] While many opportunities exist with a changing climate, economic prospects are not well captured in the literature at this time.

Climate

The rate at which Alaska's temperature has been warming is twice as fast as the global average since the middle of the 20th century. Statewide average temperatures for 2014–2016 were notably warmer as compared to the last few decades,[31,32,33] with 2016 being the warmest on record. Daily record high temperatures in the contiguous United States are now occurring twice as often as record low temperatures. In Alaska, starting in the 1990s, high temperature records occurred three times as often as record lows, and in 2015, an astounding nine times as frequently.[34,35]

Statewide annual average temperatures from 1925 to the late 1970s were variable with no clear pattern of change;[36] however, beginning in the late 1970s and continuing at least through the end of 2016, Alaska statewide annual average temperatures began to increase, with an average rate of 0.7°F per decade, (Taylor et al. 2017,[37] after Hartmann and Wendler 2005;[38] see Figure 26.1). Temperatures have been increasing faster in Arctic Alaska than in the temperate southern part of the state, with the Alaska North Slope warming at 2.6 times the rate of the continental U.S. and with many other areas of Alaska, most notably the west coast, central interior, and Bristol Bay, warming at more than twice the continental U.S. rate.[39] The long-term temperature trends, however, include considerable variability from decade to decade. For example, in the early part of the record (1920s to early 1940s), temperatures were moderate statewide, with annual averages generally near the long-term average, but were lower from about 1945 to about 1976 and then increased rapidly in the 1970s and 1980s and again in the mid-2010s (Figure 26.1). These variations are in part consistent with variations in large-scale patterns of climate variability in the Pacific Ocean;[40] in particular, Arctic warming in the early 20th century was intensified by Pacific variability (warm and cold anomalies of the Pacific sea surface temperatures).[41] Precipitation changes have

Observed and Projected Changes in Annual Average Temperature

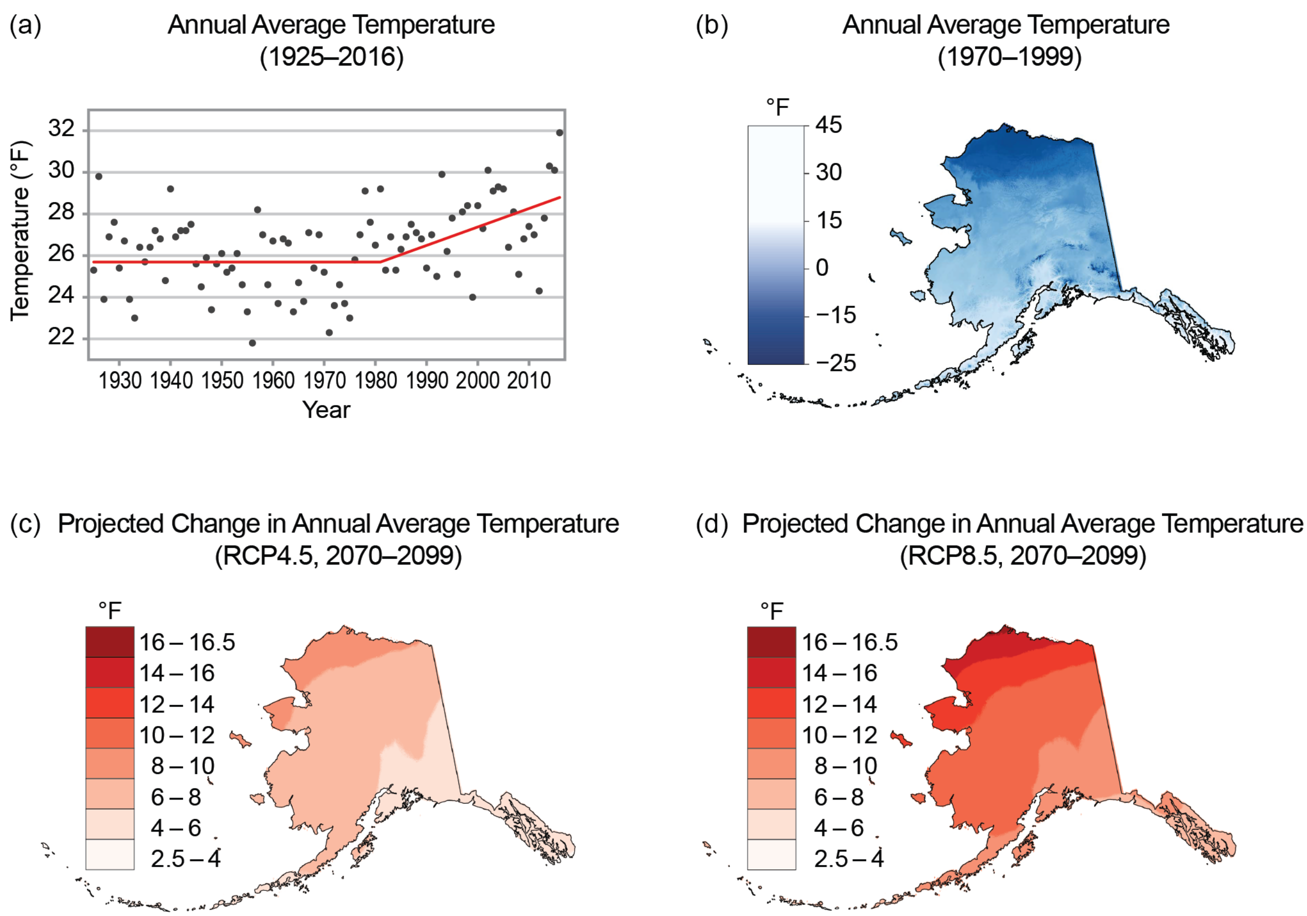


Figure 26.1: (a) The graph shows Alaska statewide annual average temperatures for 1925–2016. The record shows no clear change from 1925 to 1976 due to high variability, but from 1976–2016 a clear trend of +0.7°F per decade is evident. (b) The map shows 1970–1999 annual average temperature. Alaska has a diverse climate, much warmer in the southeast and southwest than on the North Slope (c) The map shows projected changes from climate models in annual average temperature for end of the 21st century (compared to the 1970–1999 average) under a lower scenario (RCP4.5). (d) The map is the same as (c) but for a higher scenario (RCP8.5). Sources: (a) National Oceanic and Atmospheric Administration and U.S. Geological Survey, (b–d) U.S. Geological Survey.

varied significantly across the state from 1920 to 2012, with long-term trends generally showing no clear pattern of change.[39]

Projected Temperature and Precipitation Changes

Recent availability of more localized climate information allows for more complete descriptions of the geographical variation in historical trends and climate projections.[39,42,43] Using downscaled global climate models[43] and the higher scenario (RCP8.5) (see Ch. 2: Climate, Box 2.7 and the Scenario Products section of App. 3),[44] more warming is projected in the Arctic and interior areas than in the southern areas of Alaska, and average annual precipitation increases are projected for all areas of the state, with greater increases in the Arctic and interior and the largest increases in the northeastern interior.

Climatic extremes are expected to change with the changing climate. Under a higher scenario (RCP8.5), by mid-century (2046–2065) the highest daily maximum temperature (the hottest temperature one might expect on a given summer day) is projected to increase 4°–8°F compared to the average for 1981–2000. For the same future period (2046–2065), the lowest daily maximum temperature (the highest temperature of the coldest day of the year) throughout most of the state is projected to increase by more than 10°F, with smaller projected changes in the Aleutian Islands and southeastern Alaska. Additionally, the lowest daily minimum temperatures (the coldest nights of the year) are projected to increase by more than 12°F. The number of nights below freezing would likely decrease by at least 20 nights per year statewide, and by greater than 45 nights annually in coastal areas of the North Slope, Seward Peninsula, Yukon–Kuskokwim Delta, Alaska Peninsula, and Southcentral Alaska.[45] Annual maximum one-day precipitation is projected to increase by 5%–10% in southeastern Alaska and by more than 15% in the rest of the state, although the longest dry and wet spells are not expected to change over most of the state.[45] Growing season length (the time between last and first frosts in a given year) is expected to increase by at least 20 days and perhaps more than 40 days compared to the 1982–2010 average.[35] Whether or not this increased growing potential is realized will largely depend on soil conditions and precipitation.

Key Message 1

Marine Ecosystems

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

Arctic sea ice—its presence or absence and year-to-year changes in extent, duration, and thickness—in conjunction with increasing ocean temperatures and ocean acidification, affects a number of marine ecosystems and their inhabitants, including marine mammals, the distribution of marine Alaska fish and their food sources.[37]

Arctic Sea Ice Continues to Change

Since the early 1980s, annual average arctic sea ice extent has decreased between 3.5% and 4.1% per decade, and September sea ice extent, which is the annual minimum extent, has decreased between 10.7% and 15.9% per decade. As the climate continues to warm, it is likely that there will be a sea ice-free Arctic during the summer within this century.[37,46]

Sea ice provides an important surface for algal production and growth in marine ecosystems during spring. This production beneath the sea ice is an important source of carbon for pelagic (mid- to upper-water column) grazers, such as copepods and krill, and for benthic (lower-water) detritivores, such as clams and worms that feed on dead, organic material.[47,48] In turn, the abundance of these animals provides food for higher trophic-level organisms such as fish, birds, and mammals in regional marine ecosystems. The presence or absence of sea ice affects the transfer of heat, water temperature, and nutrient transport, as well as other processes (such as the breakdown or transformation of organic matter into its simplest inorganic forms) that affect ecosystem productivity.[49] In the Arctic, higher-level organisms such as Arctic cod,[17] polar bears, and walruses[50,51,52,53] are dependent upon sea ice for foraging, reproduction, and resting and are directly affected by sea ice loss and thinning (Box 26.1).

Box 26.1: Polar Bears and Walruses

Polar bears and walruses are both dependent on sea ice during parts of their lives. Polar bears rely on sea ice to access prey and establish maternal dens, and Pacific walruses rely on drifting sea ice as a platform to rest on between foraging dives. Changes in the distribution of seasonal sea ice have resulted in changes in the behavior, migration, distribution, and, in some areas, population dynamics of both species. Changes in spring ice melt have affected the ability of Alaska coastal communities to meet their walrus harvest needs, resulting in low harvest levels in several recent years. Ongoing research seeks to forecast the population-level consequences of sea ice changes for polar bears and walruses by studying the animals' behavior changes, especially in response to increased shipping and changes in subsistence harvest practices. Changes in the ability of Indigenous communities to access these two species in the future may be harder to assess, but that access will be crucial for the short- and long-term hunting success and resultant well-being of the communities.

Figure 26.2: (a) An adult female polar bear and cub are shown near Kaktovik, Alaska, in September 2015. (b) Walruses gathered on the shores of the Chukchi Sea near Point Lay, Alaska, in September 2013. Photo credits: (a) Stewart Breck, USDA (b) Ryan Kingsbery, USGS.

Ocean Acidification

The oceans are becoming more acidic (known as ocean acidification) in an emerging global problem that will intensify with continued carbon dioxide (CO_2) emissions (Ch. 9: Oceans, KM 1 and 2). Ocean acidification negatively affects organisms such as corals, crustaceans, crabs, mollusks, and other calcium carbonate-dependent organisms such as pteropods (free-swimming pelagic sea snails and sea slugs), the latter being an important part of the food web in Alaska waters. Some studies in the nutrient-rich regions have found that food supply may play a role in determining the resistance of some organisms to ocean acidification.[54]

Changes in ocean chemistry and increased corrosiveness are exacerbated by sea ice melt, respiration of organic matter, upwelling, and glacial runoff and riverine inputs, thus making the high-latitude North Pacific and the western Arctic Ocean (and especially the continental shelves of the Bering, Chukchi, and Beaufort Seas; see Figure 26.3) particularly vulnerable to the effects of ocean acidification. Also, more ice-free water will indirectly allow for greater uptake of atmospheric CO_2.[18,55,56] More recent research suggests that corrosive conditions have been expanding deeper into the Arctic Basin over the last several decades.[57] The annual average aragonite saturation state (a metric used to assess ocean acidification) for the Beaufort Sea surface waters likely crossed the saturation horizon near 2001),[18] meaning that the Beaufort Sea is undersaturated (lacking sufficient concentrations of aragonite) most of the year—a condition that limits the ability of many marine species to form shells or skeletons (Figure 26.3). Under the higher scenario (RCP8.5), the Chukchi Sea is projected to first cross this threshold around 2030 and then remain under the threshold after the early 2040s, and the Bering Sea will likely cross and remain under the threshold around 2065 (Figure 26.3).[18]

Through lab experiments, ocean acidification has been shown to affect the growth, survival, sensory abilities, and behavior of some species, especially species of importance to Alaska, such as Tanner and red king crab and pink salmon.[58,59,60,61,62] Studies indicate flatfish, such as the northern rock sole, are sensitive to lowered pH (lower pH equates to higher acidity), while walleye pollock have not shown adverse effects on growth or survival.[63,64] Pteropods play a critically important role in the Alaska water food web and have been shown to be particularly susceptible to ocean acidification. The effect of ocean acidification on pteropods manifests itself as severe shell dissolution, impaired growth, and also reduced survival.[65,66] More importantly, these effects are observed in the natural environment, making pteropods one of the most susceptible indicators for ocean acidification.[65,67,68] The effects observed in pteropods can be interpreted as the early-warning signal of the impacts of ocean acidification on the ecosystem integrity, linking pteropod effects to higher trophic levels, in particular fish (such as pink salmon, sole, and herring) that are feeding on pteropods. However, the impacts on these food webs are highly uncertain[69,70,71] but can be more detrimental in the high-latitudinal ecosystems with fewer species and shorter food chains.[67,68]

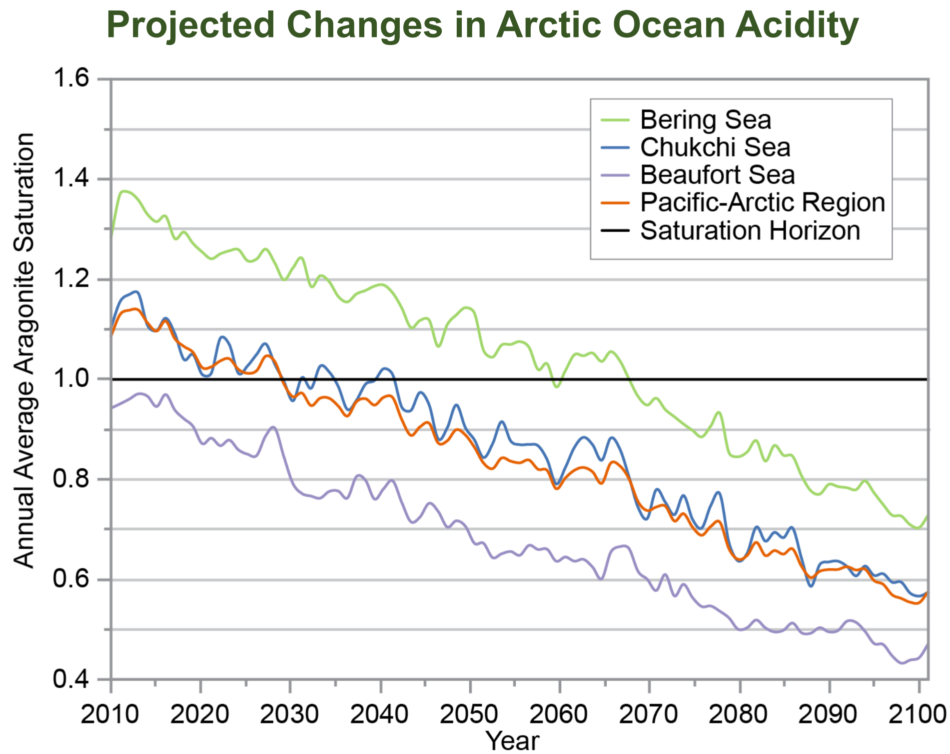


Figure 26.3: The time series shows the projected decline in the annual average aragonite saturation (one of the consequences of increased ocean acidity, or lower pH) for the Bering Sea, Chukchi Sea, Beaufort Sea, and for the entire Pacific-Arctic region under the higher scenario (RCP8.5). Aragonite saturation is a metric used to assess ocean acidification and the ability for organisms to build shells and skeletons. The annual average saturation state for the Beaufort Sea surface waters likely crossed the saturation horizon—a tipping point—around 2001, meaning it is currently undersaturated and its marine ecosystems are vulnerable to the impacts of ocean acidification during most of the year. The Chukchi Sea is projected to first cross this threshold around 2030 and then likely remain under the threshold after the early 2040s; the Bering Sea is projected to be a concern after 2065. Source: adapted from Mathis et al. 2015.[18]

Alaska Fishes

More than 600 fish species have been found in Alaska waters,[72] and Alaska's industrial fisheries in the Gulf of Alaska and Bering Sea are among the most productive and valuable in the world, with an estimated average of $5.9 billion of total economic activity in 2013–2014 (in 2013–2014 dollars).[73,74] Climate effects on Alaska's marine ecosystems are of considerable economic interest because of their impacts on the commercial harvests from the Northeast Pacific and subsistence fisheries for salmon, char, whitefishes, and ciscos in the Arctic and on these species or others elsewhere in the state.

The distribution of many ocean fish species is shifting northward as the ranges of warmer-water species expand and colder-water species contract in response to rising ocean temperatures (Ch. 9: Oceans, KM 2), with the confirmed presence of 20 new species and 59 range changes in the last 15 years in the Chukchi and Beaufort Seas.[17] In the Bering Sea, Alaska pollock, snow crab, and Pacific halibut have generally shifted away from the coast and farther from shore since the early 1980s.[75] These changes reflect possible northward shifts in species distributions, particularly in the Bering Strait region.[76]

Marine ecosystem food webs are also being affected by climate change. Changes in sea ice cover and transport of warmer seawater and drifting organisms (such as plankton, bacteria, and marine algae) may be impacting how surface ocean waters interact with the bottom ocean waters, especially over the shallow northern Bering and Chukchi Sea

Changes to North Pacific Marine Ecosystems in a Warming Climate

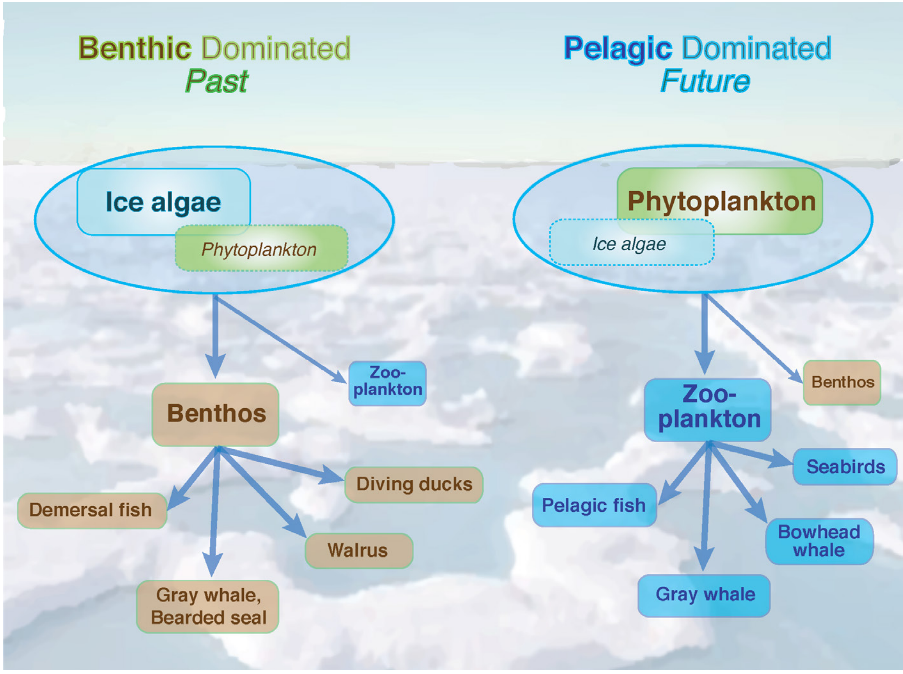


Figure 26.4: As sea ice thins and retreats earlier in the season, it is anticipated that food webs under the ice will switch from a benthic-dominated (lower in the water to seafloor) to a pelagic-dominated (middle to higher in the water) marine ecosystem. Source: Moore and Stabeno 2015.[78]

shelves. As relatively larger organisms (such as zooplankton, which are very tiny marine animals in the water column) become more abundant, they are able to efficiently graze on the smaller plant organisms (such as phytoplankton—microscopic marine plants) and reduce the amount of food supplied to the bottom sediments. This in turn can impact benthic animals that are important prey to marine mammals, such as walrus, gray whales, and bearded seals.[77,78,79] A switch from benthic (lower) to pelagic (upper) marine ecosystem activities that link organisms and their environment, in combination with warmer temperatures, may result in this northern shelf region changing from a benthic-dominated to a pelagic-dominated marine ecosystem (Figure 26.4) and becoming a hotspot of invasion, expansion, and increased abundance of fish species such as pollock and Pacific salmon.[79] The changing conditions confer physiological and competitive benefits to species favoring warmer water conditions, such as saffron cod, and potential negative impacts to Arctic cod populations, a keystone species in Chukchi and Beaufort Seas food webs.[17]

Changes in climate-related events are likely to affect management actions and economic drivers, including fisheries, in complex ways.[80] An example is the recent heat wave in the Gulf of Alaska, which led to an inability of the fishery to harvest the Pacific cod quota in 2016 and 2017 and to an approximately 80% reduction in the allowable quota in 2018.[81] These reductions are having significant impacts on Alaska fishing communities and led the governor of Alaska to ask the Federal Government to declare a fisheries disaster. Events such as these are requiring the use of multiple, alternative models to appropriately characterize uncertainty in future population trends and fishery harvests.[82] The need to address uncertainty is especially true for the Eastern Bering Sea pollock fishery, which is one of the largest in the United States.[83] While most scientists agree that walleye pollock populations in the eastern Bering Sea are likely to decrease in a warming climate,[84,85,86,87,88] these effects can be mitigated to some extent by adopting alternative fish harvest strategies,[89] and economic losses may be partially offset by increased pollock prices.[90]

Key Message 2

Terrestrial Processes

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

As temperatures increase across the Alaska landscape, physical and biological changes are also occurring throughout Alaska's terrestrial ecosystems. Degradation of permafrost (soil at or below the freezing point of water [32°F] for two or more years) is expected to continue, with associated impacts to infrastructure,[91] river and stream discharge,[92] water quality,[93,94] and fish and wildlife habitat. Wildfires and temperature increases have caused changes in forest types from coniferous to deciduous in interior Alaska, and these changes are projected to continue with increased future warming and fire.[95,96] In tundra ecosystems, temperature increases have allowed an increase of shrub-dominated lands.[97,98] With the late-summer sea ice edge located farther north than it used to be, storms produce larger waves and cause more coastal erosion.[19] In addition, ice that does form is very thin and easily broken up, giving waves more access to the coastline.[99] A significant increase in the number of coastal erosion events has been observed as the protective sea ice embankment is no longer present during the fall months.[100] In addition, glaciers continue to diminish, and associated runoff influences other terrestrial ecosystems.[101]

Permafrost

About half of Alaska is underlain by permafrost—an essential geographic quality that affects landscape patterns and processes,[102] and construction in the Arctic depends on the ability of permafrost to remain frozen. Since the 1970s, Arctic and boreal regions in Alaska have experienced rapid rates of warming and thawing of permafrost,[103,104,105,106] with spatial modeling[107] projecting that near-surface permafrost will likely disappear on 16% to 24% of the landscape by the end of the 21st century.[108] Confidence in these estimates is higher than for those in the Third National Climate Assessment[109] due to more field sample sites, higher resolution imagery for mapping, and advanced geographic modeling techniques.

Permafrost degradation impacts society in both tangible and intangible ways. Physical impacts of thawing permafrost include unsafe food storage and preservation (Box 26.2), decreased bearing capacities of building and pipeline foundations, damage to road surfaces, deterioration of reservoirs and impoundments that rely on permafrost for wastewater containment, reduced operation of ice and snow roads in winter, and damage to linear infrastructure (such as roads and power lines) from landslides.[20] As permafrost thaws, the ground sinks (known as subsidence), causing damage to buildings, roads, and other infrastructure;[110,111,112] these impacts to structures and facilities are likely to increase in the future.[91] In addition to physical impacts, thawing permafrost has important societal impacts that cannot be quantified. The loss of cultural heritage for Alaska's Indigenous people includes the loss of archaeological sites, structures, and objects, as well as traditional cultural properties, which affects their ability to connect to their ancestors and their past.[113]

Box 26.2: Iñupiat Work to Preserve Food and Traditions on Alaska's North Slope

Local traditional foods are important for nutritional, spiritual, cultural, and social benefits. Many of these foods are sometimes stored in traditional underground ice cellars kept cold by the surrounding permafrost. With warming climate conditions, many of these ice cellars are beginning to thaw, increasing the risks for foodborne illness, food spoilage, and even injury from structural failure. The Iñupiat community of Nuiqsut, located on Alaska's North Slope, is among the communities using new technology to improve the storage environment in existing cellars. Find out more at https://toolkit.climate.gov/case-studies/i%C3%B1upiaq-work-preserve-food-and-traditions-alaskas-north-slope.

Wildfire

The annual area burned by wildfires in Alaska varies greatly year-to-year, but the frequency of big fire years (larger than 2 million acres) has been increasing—with three out of the top four fire years (in terms of acres burned) in Alaska occurring since the year 2000.[114] As a result, the vegetation of forested Interior Alaska now has less acreage of older spruce forest and more of post-fire early successional vegetation, birch, and aspen than it did prior to 1990.[95] This change favors shrub-adapted wildlife species such as moose but also destroys the slow-growing lichens and associated high-quality winter range that caribou prefer, though the effects of fire-driven habitat changes to caribou population dynamics are uncertain.[23] Some rural communities, however, have adapted to these vegetation changes by designing small-scale programs that enhance moose browsing (feeding on leaves, twigs, or tree branches) or developing biofuel infrastructure integrated with fire prevention tactics.[115,116] In addition to range expansion due to changes in wildfire, shrubs have been increasing in density and height in tundra environments due to increasing temperatures,[98] with shrub expansion in tundra ecosystems being observed across the North American Arctic.[117,118] Shrub-adapted wildlife species such as moose and snowshoe hares, and in some cases beaver, have followed the expansion of shrubs and are now common in parts of Arctic Alaska and Canada, where they were previously rare or absent.[24,119,120] The area burned by wildfires may increase further under a warming climate.[25] Projections of burned area for 2006–2100 are estimated at 98 million acres under a lower scenario (RCP4.5) and 120 million acres under a higher scenario (RCP8.5).

Coastal and River Erosion

Flooding and erosion of coastal and river areas affect over 87% of the Alaska Native communities,[121,122,123,124,125] with some coastal areas being threatened due to changes in sea ice and increased storm intensity as a result of climate change.[122,126] Offshore and landfast sea ice is forming later in the season, which allows coastal storm waves to build while leaving beaches unprotected from wave action.[99,126,127,128,129] Rates of erosion vary throughout the state, with the highest rates measured on the Arctic coastline at more than 59 feet per year (Figure 26.5).[19] For context, one study noted that rates of coastal erosion may have varied from location to location but could have been more than 100 feet per year at the Canning River between Camden Bay and Prudhoe Bay.[130] Other researchers have come up with different rates along the Alaska Arctic coast.[19] Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to worsen flooding and accelerate erosion in many regions, leading to the loss of terrestrial habitat and cultural resources and requiring entire communities, such as Kivalina in northwestern Alaska (Ch. 1: Overview, Figure 1.18),[131] to relocate to safer terrain.[19,122,123]

Erosion Rates Along Alaska's North Coast

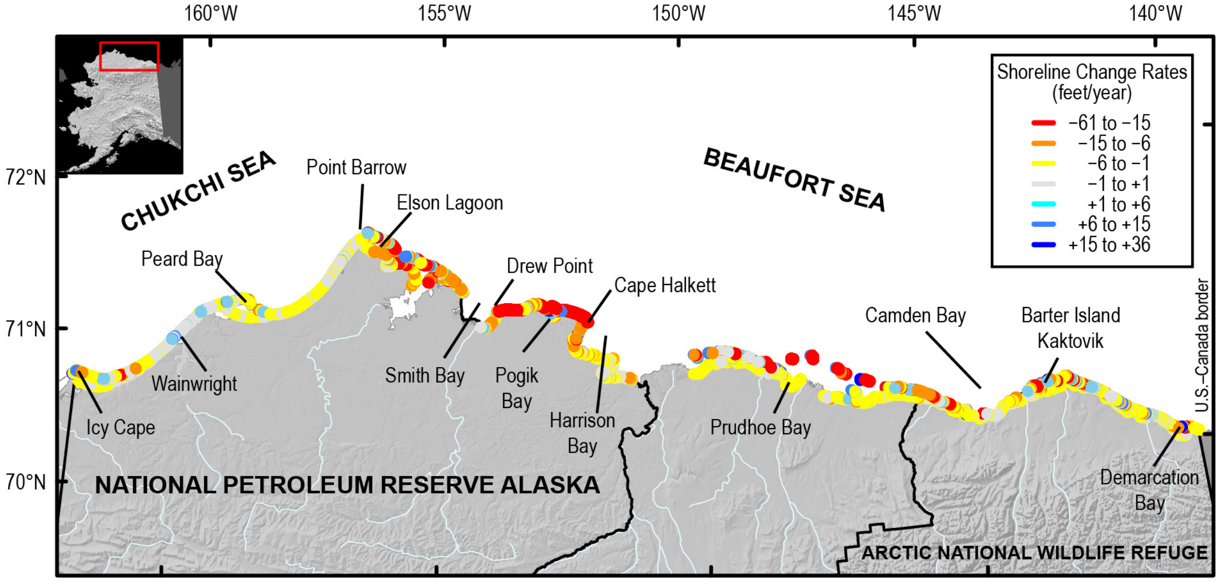


Figure 26.5: The map is of the north coast of Alaska and shows color-coded shoreline erosion rates, which can lead to the loss of habitat, cultural resources, and infrastructure. Source: adapted from Gibbs and Richmond 2015.[19]

Many Alaska communities that are not located on the coast are adjacent to large rivers, where riverine erosion is a serious problem,[123] with some communities (for example, Minto in 1969 and Eagle in 2009) having to relocate housing and other infrastructure due to erosion and associated flooding. Erosion rates vary, but conservative rates for the Ninglick River at Newtok range from 36 feet per year (west/downstream) to 83 feet per year (east/upstream), although actual observations by Newtok residents indicate a potential rate as high as 110 feet per year.[132] This has required the residents of Newtok to move to the new site of Mertarvik, about 9 miles away.[133]

In both coastal and river communities, various types of infrastructure and cultural resources are being threatened. A number of adaptation measures are being pursued or proposed[134,135] that include relocation, the construction of rock walls, the use of sandbags, and the placement of various forms of riprap, which may only slow or displace the erosion process and in some cases be maladaptive.[100,123]

Glacier Change

Glaciers continue to melt in Alaska, with an estimated loss of 75 ± 11 gigatons (Gt) of ice volume per year from 1994 to 2013,[136,137] 70% of which is coming from land-terminating glaciers; this rate is nearly double the 1962–2006 rate.[138] Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,[139,140,141,142] with the potential to alter streamflow along the Gulf of Alaska[143] and to change Gulf of Alaska nearshore food webs.[144]

Melting glaciers are likely to produce uncertainties for hydrologic power generation,[22] which is an important resource in Alaska.[145,146] In the short term, melting glaciers can increase hydropower capacity by increasing downstream flow; however, with continued melting there will likely be less meltwater for the future. This may be offset by an increase in precipitation in Alaska,[45] although an increase in precipitation does not necessarily lead to increases in catchment runoff (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5).[147]

Key Message 3

Human Health

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

The influence of climate change on human health in Alaska can be traced to three sources: direct exposures, indirect effects, and social or psychological disruption. Each of these will have different manifestations for Alaskans when compared to residents elsewhere in the United States.

Direct Exposures

In general, even with a warming climate, Alaska is not expected to experience the extremes of heat and humidity found at lower latitudes; however, rising temperatures do pose a risk. Air conditioning in homes is rare in Alaska, so relief is seldom available for at-risk persons to escape high temperatures or from smoke exposure due to wildfires, assuming proper filters are not installed.

Winter travel has long been a key feature of subsistence food gathering activities for rural Alaska communities. Higher winter temperatures and shorter durations of ice seasons may delay or disrupt usual patterns of ice formation on rivers, lakes, and the ocean. For hunters and other travelers, this increases the risk of falling through the ice, having unplanned trip extensions, or attempting dangerous routes, leading to exposure injury, deaths, or drowning (Box 26.3).[26,148] Community search and rescue workers experience similar risks in searching for missing travelers, extending the threat across communities. Adaptation strategies being promoted include improved communication about local ice and water conditions, increasing use of survival suits and personal floatation devices,[149] and the use of personal locator beacons and messaging devices that can alert responders to a traveler at risk or provide reassurance and avoid unneeded search and rescue operations in high-risk conditions.[150]

Extreme weather events such as major storms, floods, and heavy rain events have all occurred in Alaska with resulting threats to human health.[153,154] For coastal areas, the damage from late-fall or winter storms is likely to be compounded by a lack of sea ice cover, high tides, and rising sea levels, which can increase structural damage to tank farms, homes, and buildings and can threaten loss of life from flooding. Such events can damage vital water and sanitation systems in several ways, including saltwater intrusion of drinking water sources, loss of power leading to freezing and damage to water and sewer systems, or disruptions to community septic drain fields and water distribution systems. These events would all reduce access to water/sewer services, leading to an increased risk of water-related infectious diseases.[155] Similar events threaten communities on rivers, where flooding due to increased glacial melt or heavy rains can cause extensive structural damage and loss of life. It is uncertain if climate warming will increase severe mid-winter ice jam events or reduce their hazards due to more gradual melting of ice with earlier spring thaws.[156] Improved real-time observations and river breakup forecasts are now available for use by decision-makers to help prepare in advance of

Box 26.3: Climate Change and Public Health

Environmental changes from a warming climate, such as unpredictable weather that greatly deviates from the norm, can significantly affect the physical and mental health of rural Alaskans. They may face difficulty harvesting local food and hazardous travel across the landscape. These climate-related challenges are being addressed by the Alaska Native Tribal Health Consortium Center for Climate and Health, which is working to recognize these new vulnerabilities and to support healthy adaptation strategies. Outcomes and activities from this effort include

- the One Health Group, which consists of federal, state, and nongovernmental organizations, conducts quarterly webinars and presentations on the intersection between human, animal, and environmental health. Cosponsored by the Centers for Disease Control and Prevention, this forum improves communication and situational awareness about climate change and public health in Alaska;[151]

- the Local Environmental Observer (LEO) Network,[6] a forum funded by the Environmental Protection Agency, the Department of the Interior, and the Bureau of Ocean Energy Management, is used for tracking local observations of environmental events and connecting communities with technical resources using an internet-based mapping tool and smartphone applications;

- comprehensive climate vulnerability assessments of rural Alaska communities;[152] and

- an electronic newsletter, *Northern Climate Observer*, which provides weekly access to articles and observations about the circumpolar north.[152]

More can be learned about these Alaska health-related resources at: https://toolkit.climate.gov/case-studies/addressing-links-between-climate-and-public-health-alaska-native-villages

potential flood events; such systems could help communities reduce the negative effects of seasonal flooding.[157]

Climate-driven increases in air pollution in Alaska are primarily linked to the increases in wildfire frequency and intensity. Wildfires, however, threaten individual safety in adjacent communities and pose risks downwind from smoke inhalation, particularly for children and persons with chronic respiratory and cardiovascular conditions (Ch. 13: Air Quality, KM 2; Ch. 14: Human Health, KM 1).[10,158] Adaptations to protect persons at risk from wildfire exposure include using community air quality indices linked to recommendations for specific groups, educating people about outdoor activities and use of masks, and creating a “clean room” using high-efficiency particulate air (HEPA) dust filters or air conditioning.[159] It is also likely that there will be an increased risk of respiratory allergies related to longer and more intense seasonal pollen blooms and mold counts (Ch. 13: Air Quality, KM 3).[160] Public reporting of pollen counts conducted in Anchorage and Fairbanks[161] is used to advise allergy sufferers of increasing risks and is linked to recommendations to avoid exposure and reduce symptoms. Increased respiratory symptoms have also been reported in communities that are experiencing increased windblown dust. Adaptations include dust suppression, improving indoor air quality, and use of masks.

Indirect Effects

Climate change has indirect effects on human health in Alaska through changes to water, air, and soil and through ecosystem changes affecting the range and concentration of disease-spreading animals and food security, especially in rural communities (Ch. 14: Human Health, KM 1). These changes can result in positive and negative health effects; many are site specific, and documentation is highly dependent on availability of monitoring or reporting data.

In-home water and sanitation services are a fundamental contributor to health, and the absence of such services in 15% of rural Alaska homes is associated with increased risk of gastrointestinal, respiratory, and skin infections.[155,162,163] Climate-related environmental changes that can affect access to water and sanitation services have been well-documented.[154] These changes include loss of surface water through drainage of tundra ponds, lower source-water quality through increased riverbank erosion due to permafrost thaw or saltwater intrusion in coastal communities, and increased coastal erosion or storm surge leading to wastewater treatment system damage.[164] Permafrost thawing poses a threat to centralized water and wastewater distribution systems that need stable foundations to maintain system integrity. More flexible service connections have been used to reduce damage from movement caused by permafrost thawing.[165] People cope with water shortages by use of rainwater catchment or other untreated water sources, reuse of water used for clothes or personal hygiene, or rationing of water to prioritize drinking and cooking. Such practices, however, could lead to increased risk of waterborne infectious diseases or increased spread of person-to-person infections through decreased hygiene. Increased silt or organic material in source water can quickly clog filters, increasing costs of water treatment. This can result in reduced filtration effectiveness and increased exposure to waterborne pathogens, such as *Giardia intestinalis*.[165] The state of Alaska is funding development and testing of decentralized water and sanitation systems that use in-home treatment, water reuse, and other efficiencies that may be an alternative in homes without existing services or if centralized systems fail.[166]

Changes in insect and arthropod ranges due to climate change have raised human health concerns, such as the documented increase in venomous insect stings in Alaska.[167,168] Tick-borne human illnesses are uncommon in Alaska, but new reports of ticks on domestic dogs without travel exposure outside Alaska raise concerns about tick range extension into Alaska and the potential for introduction of new pathogens.[169] Several human infectious diseases could potentially expand in a changing Alaska climate. For example, climate change may allow some parasites to survive longer periods, provide an increase in the annual reproduction cycles of some disease-carrying insects and pests (vectors), or allow infected host animal species to survive winters in larger numbers, all increasing the opportunity for transmission of infection to humans.[170] However, some of these diseases are rare, and detecting increases is hampered by Alaska's small population, limited access to diagnostic testing, and the absence of surveillance for some human illness (for example, toxoplasmosis, an infection caused by a parasite). Foodborne pathogens, including parasites, have been identified as likely to increase due to increased temperature changes and increasing exposure.[171,172] In Alaska, disruption of ice cellars from thawing permafrost and coastal erosion has raised concerns about food spoilage or infectious outbreaks, but documented human illness events are lacking. Likewise, the documented northward range expansion of beavers has been postulated to increase the threat of waterborne *Giardia* infections in humans; however, human *Giardia* illness reports have been stable in Alaska and show no increasing regional trends.[173] Emerging infectious threats led to the formation of an Alaska One Health Group, which meets quarterly to combine perspectives from human, animal, and environmental health and uses new data generated from the Local Environmental Observer (LEO) Network.[6,174] A new rural monitoring program has been developed for tribal community settings to include collection of data on infectious threats from food, animals, and water.[175]

Harmful algal blooms (HABs) produce toxins that can harm wildlife and pose a health risk to humans through consumption of contaminated shellfish. Because phytoplankton growth is increased in part by higher water temperatures, risks for HAB-related illnesses, including paralytic shellfish poisoning (PSP), may increase with climate change. PSP is a long-recognized, untreatable, and potentially fatal illness caused by a potent neurotoxin in shellfish. PSP illnesses are considered a public health emergency. Two approaches are being used to reduce PSP in Alaska. First, because recreational shellfish harvesting is very popular in Alaska (see Ch. 24: Northwest, KM 2 and 4 and Figure 24.7), some communities have begun to monitor for PSP toxins among shellfish at locations used for noncommercial harvests using a "catch, hold, and test" approach, which, if coupled with reliable testing methods, could provide a strategy to reduce risk and maintain these important local harvests.[176] The second adaptation approach uses local water temperature data to predict the risk of HAB growth in Kachemak Bay. The effectiveness of these methods for reducing human health risk has not been established.[7]

An example of climate-associated disease emergence and response is the 2004 outbreak of acute gastroenteritis that was associated with consumption of raw farmed oysters contaminated by the bacterium *Vibrio parahaemolyticus*. This is a well-recognized threat in warmer coastal waters of North America but was previously unreported in Alaska. However, in 2004, surface water temperatures above shellfish beds had warmed enough to support *V. parahaemolyticus* growth. This warming was part of a documented long-term warming trend, and the outbreak is indicative of a northward range extension of this pathogen by about 600 miles.[177] In response to the outbreak, the State of Alaska developed a control plan that includes water temperature monitoring around commercial oyster beds and uses threshold-based responses to reduce health risks from this pathogen.[176] Fortunately, *V. parahaemolyticus* contamination has not become a major health threat. Alaska has averaged only three reported cases per year since the first outbreak, and many of these are traceable to non-Alaska shellfish; however, the projected rise in sea surface temperatures in Alaska will favor increased *Vibrio* growth and seasonal range expansion with an increased risk of human exposure and illness.[178,179]

Psychological and Social Effects

Climate change is a common concern among Alaskans and is associated with feelings of depression and uncertainty about the potential changes to communities, subsistence foods, culture, and traditional knowledge and the potential of relocation from long-established traditional sites.[122] These uncertainties and threats have effects on mental health and on family and community relationships and may lead to unhealthy responses such as substance abuse and self-harm.[180] This is especially true of Indigenous peoples, who have a deep connection to their home areas, often described as sense of place.[181,182,183,184] Over generations, Indigenous communities have developed extensive knowledge about their areas and the plants and animals with which they share an ecosystem.[185] As the effects of climate change are felt in the landscape, many Alaska Natives feel a sense of personal loss as the familiar has become unpredictable and sometimes strange.[125] This uncertainty has also reduced traditional camping activities that strengthen community ties. Damage or loss to cultural sites and properties is also a great concern, reducing the sense of cultural continuity in one's place along with information about living and adapting there. In the context of many other social, technological, economic, and cultural changes affecting Indigenous communities, the continuation of traditional activities in traditional places can be a bedrock of stability. When this, too, is threatened, a wider sense of environmental security is at risk.[125] Community relocation or the movement of persons away from climate-threatened areas can have intergenerational effects through loss of cultural connections and adverse childhood experiences leading to poorer health outcomes. The Alaskans most vulnerable to these climate-related changes are those who are most dependent on subsistence foods, the poor, the very young, the elderly, and those with existing health conditions that require ongoing care, that limit mobility, or that reduce capacity to accommodate changes in diet, family support, or stress.[11]

Key Message 4

Indigenous Peoples

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

Alaska's climate is changing rapidly, with far-reaching effects throughout the state, including in its Indigenous communities. Alaska's rural communities are predominantly inhabited by Indigenous peoples, with some of them disproportionately vulnerable to socio-economic and environmental change; however, they also have rich cultural traditions of resilience and adaptation.[109,125,134,186,187,188] The impacts of climate change are likely to affect all aspects of Alaska Native societies, from nutrition, infrastructure (see Key Message 2), economics, and health consequences to language, education, and the communities themselves. Most of these impacts are also experienced in other rural, predominantly nonnative communities in Alaska and are therefore covered in other sections of this chapter.

Subsistence Activities

Subsistence hunting, fishing, and gathering provide hundreds of pounds of food per person per year in many Alaska Native villages.[189,190] Producing, preparing, sharing, and consuming these foods provide a wealth of nutritional, spiritual, cultural, social, and economic benefits. Traditional foods are widely shared within and between communities and are a way of strengthening social ties.[191,192,193] Climate change is altering the physical setting in which these subsistence activities are conducted.[15,182] Examples include

- reducing the presence of shore-fast ice used as a platform to hunt seals[194] or butcher whales,[195]
- reducing the availability of suitable ice conditions for hunting seals and walrus (Figure 26.6),[28] and
- exacerbating the risks of winter travel due to increasing areas of thin ice and large fractures within the sea ice (commonly referred to as "leads") as well as water on rivers.[26,27,196]

However, climate change is also providing more opportunity to hunt from boats late in the fall season or earlier in spring.[125] Increasing temperatures affect animal distribution and can alter the availability of subsistence resources, often making hunting and fishing harder but sometimes providing new opportunities, such as fall whaling on St. Lawrence Island.[197] Shellfish populations, an important subsistence and commercial resource along the Alaska coast, have been declining for more than 20 years throughout coastal Alaska, with ocean warming and ocean acidification (Ch. 9: Oceans) contributing to the decline (see Key Message 1). Warm temperatures and increased humidity are also affecting ice cellars used traditionally to store food (as noted earlier in this chapter), thereby making it harder to air-dry meat and fish on outdoor racks, causing food contamination.[131,198] Some communities have found new storage methods or have changed to an increasingly Western diet. Subsistence foods decrease the costs of feeding a family compared to purchased foods, which in rural Alaska are almost twice the cost of those in Anchorage.[199,200] One net result of all these changes is an overall decrease in food security for residents of rural Alaska Native communities (Ch. 10: Ag & Rural, KM 4).[29]

Thawing permafrost in the boreal forest has accelerated land and riverbank erosion (see Key Message 2). Subsistence harvesters have expressed concern that less precipitation is resulting in rivers becoming shallower and lakes drying.[15] The increasingly dynamic nature of interior river characteristics has contributed to more challenging boat navigability and less dependable locations for fish wheel and net sets. These climate-induced environmental changes also occur in the context of other regulatory, social, administrative, legal, and economic constraints, which affect the ways that climate change impacts manifest themselves in specific locations.[201] As the environment changes, overall well-being can

Variable Weather Affects Harvest Levels

Figure 26.6: These images of marine mammal meat drying on racks in Gambell, Alaska, in (a) June 2012 and (b) July 2013 illustrate the interannual variability of harvests due to sea ice and weather conditions and suggest what the future may hold if ice and weather trends continue. Photo credit: Henry P. Huntington.

also suffer from the sense of dislocation and from losing the spiritual and cultural benefits of providing and sharing traditional foods, as these activities do much to tie communities together.[202,203,204]

Adaptation Actions

In the midst of negative impacts from climate change, Alaska Native communities display remarkable capacity for response and adaptation (Ch. 15: Tribes, KM 3).[29,125,205] Sometimes, adaptation means expanding networks for sharing of foods and ideas, as has been seen in the Kuskokwim River area;[206] applying Indigenous evidence and approaches to habitat protection;[27] or giving communities more say in identifying priorities for action and directing available funds for community needs and action-oriented science.[125] A clear example is the community of Shaktoolik's initiative to build a community-driven, mile-long and seven-foot-high berm made out of driftwood and gravel to protect itself from flooding and erosion during storm episodes.[207] As storms increase in frequency and intensity,[126] some builders in Gambell, Alaska, are considering efficient house designs that avoid exposure to prevailing winds and piling up of snow at the doors.[208,209] While some of these initiatives are part of statewide efforts to address common threats from climate change,[210] at other times communities have been able to take advantage of new opportunities, such as expanding networks for sharing of foods and ideas,[206] fishing for new species,[211] or applying Indigenous knowledge and frameworks to habitat protection and ecosystem management.[27] Further effort is warranted both on cataloging community response to climate-related changes in the environment and on enhancing the transfer of knowledge among rural communities on innovative and effective adaptations.[212]

Key Message 5

Economic Costs

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

Climate change in Alaska has caused regionally disparate economic effects. The infrastructure and community relocation costs, along with potential adverse effects on fisheries, accrue predominantly to rural communities. While both urban and rural communities benefit from reduced space heating costs, the urban communities bear few of the costs and risks. The profound and diverse climate-driven changes in Alaska's physical environment and ecosystems generate economic impacts through their effects on environmental services. These services include positive benefits directly from ecosystems (for example, food, water, and other resources), as well as services provided directly from the physical environment (for example, temperature moderation, stable ground for supporting infrastructure, and smooth surface for overland transportation).[213] Some of these effects are relatively assured and in some cases are already occurring. Other impacts are highly uncertain, due to their dependence on the structure of global and regional economies and future human alterations to the environment[112] decades into the future, but they could be large.

Infrastructure

Threats to infrastructure in Alaska from coastal and riparian erosion caused by the combination of rising sea levels, thawing permafrost, reduced sea ice, and fall storms are well known.[214,215] A study published in 2008 projected that the cost (for 2008–2030) associated with early reconstruction and replacement of public infrastructure (roads, public buildings, airports, and rail lines) caused by damage from these threats was estimated to be between $3.6 and $6.1 billion (in 2008 dollars).[20] Assuming the 2.85% annual real interest rate used in these studies, the cost translates to an average of $250 to $420 million per year (in 2015 dollars). A more recent study estimated a somewhat smaller annual cost of $110–$270 million between 2015 and 2060 for maintenance and repair costs to mitigate or remediate damage to public infrastructure from climate warming (in 2015 dollars, discounted 3%) under the lower scenario (RCP4.5) and higher scenario (RCP8.5), respectively.[11,91] Projecting these costs to the end of the century, cumulative effects amounted to $3.7 billion under the lower scenario (RCP4.5) to $4.5 billion under the higher scenario (RCP8.5) for reactive repair and replacement, but $2.0 to $2.5 billion for proactive adaptation costs, depending on the climate change scenario[11] (in 2015 dollars, discounted 3%). The lower cost assumes that funding will be available for maintenance and repair before facilities require replacement, which is not guaranteed.[216,217] Both studies excluded losses to commercial and industrial buildings and private homes.

Coastal and riverine erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.[123] Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office study ranged from $80 to $200 million per community (dollar year not reported).[122,218] Beyond financial cost, additional challenges of relocation involve legal and policy obstacles, as well as deep cultural ties to landscape and place. Construction of rock walls, use of sandbags and riprap,[219] and replacement infrastructure for communities that are partially relocated[123] represent additional costs, as would loss of productivity and income from lack of access to utilities and drinking water and temporary displacement of residents when water and sewer lines rupture.[220,221,222]

Ice Road Transportation

In rural Alaska, where surface transportation infrastructure is extremely limited, snow and ice offer a low-cost alternative for moving people, goods, and heavy industrial equipment. As the climate warms, the resulting shorter and milder cold season reduces the season length for ice road use, increases the risk of travel on river ice, and increases the wear and tear on snow machines. Loss of overland winter transportation raises costs for extractive industries (such as oil extraction and logging) and rural Alaska households. A 2004 report estimated the cost of ice roads on the North Slope of Alaska at $100,000 per mile, versus as much as $2 million per mile for a gravel road (in 2003 dollars; $127,000 per mile for ice roads and $2.5 million for gravel in 2015 dollars).[223] Costs of foregone economic activity[103] and increased risk of winter travel are more difficult to quantify.[224]

Marine Vessel Traffic

Reduced seasonal ice has been associated with increased marine traffic in the U.S. maritime Arctic.[225] A longer ice-free shipping season could reduce the cost of shipping ore from the Red Dog mine and other mines in the region,[154,226] as well as increase certainty of shipping production facilities and equipment to North Slope oil fields. Adverse navigability effects of reduced river discharge[227] could offset beneficial effects of an extended ice-free shipping season on the cost of barge service to communities in western and northern Alaska.

Northward progression of the late-summer sea ice edge creates opportunities for increased vessel traffic of various types (including cargo and tanker ships, tour boats, and government vessels, including military)[226] to pass through the Bering Strait to or from the Northern Sea Route, the Northwest Passage,[228] and, by mid-century, directly across the Arctic Ocean.[229,230] As the Arctic Ocean opens, the Bering Strait will have increased strategic importance.[231] Lack of deep-water ports, vessel services, search and rescue operations, environmental response capabilities, and icebreaking capacity will impede expansion of vessel traffic.[225,226,230,232,233] Significant effects are likely several decades away, and new transarctic shipping will likely have little economic effects within Alaska in the near term but would bring environmental risks to fisheries and subsistence resources.[234] New oil and gas exploration and development in new areas within the U.S. economic zone are unlikely, as the Arctic Ocean waters that are not already accessible are generally off the U.S. continental shelf.

Wildfire Destroys Homes Near Willow, Alaska

Figure 26.7: The 7,220-acre Sockeye Fire near Willow, Alaska, totally destroyed 55 residences and damaged 44 in mid-June 2015. Photo courtesy of Matanuska-Susitna Borough/Stefan Hinman.

Wildfire Costs

Increasing incidence of wildfire near inhabited areas leads to a wide array of costs, including firefighting costs, health and safety impacts, property damage, insurance losses, and higher costs of fire insurance (Figure 26.7).[235] In addition, tourism businesses may experience short-term losses as visitors avoid recently burned areas. A recent estimate projected an increase in wildfire suppression costs of $25 million more per year (in 2015 dollars, 3% discount rate) under the lower scenario (RCP4.5) above the 2002–2013 annual average by the end of the century.[21] The cost could be higher if the footprint of human settlement expands and the geographic area designated for active fire suppression expands accordingly. Property damage from wildfires will likely increase as the number of large fire years increases. The Millers Reach Fire in 1996 destroyed 454 structures, including 200 homes in the Matanuska-Susitna Borough, with an estimated total cost of $80 million (in 1996 dollars; $120 million in 2015 dollars).[236] A subsequent fire in 2015 in the same general area destroyed another 55 homes and heavily damaged 44 other structures.[237]

Heating Costs

Increasing winter temperatures have reduced the demand for energy and associated costs to provide space heating for Alaska homes, businesses, and governments. Heating degree days (a measure of the energy required to heat homes and other buildings) have declined substantially in most parts of the state as compared to mid-20th century levels, including 5% in Sitka, 6% in Fairbanks and Nome, and up to 8% in Anchorage and Utqiaġvik (formerly known as Barrow; Figure 26.8).[238]

Energy Needed for Heating Decreases Across Much of Alaska

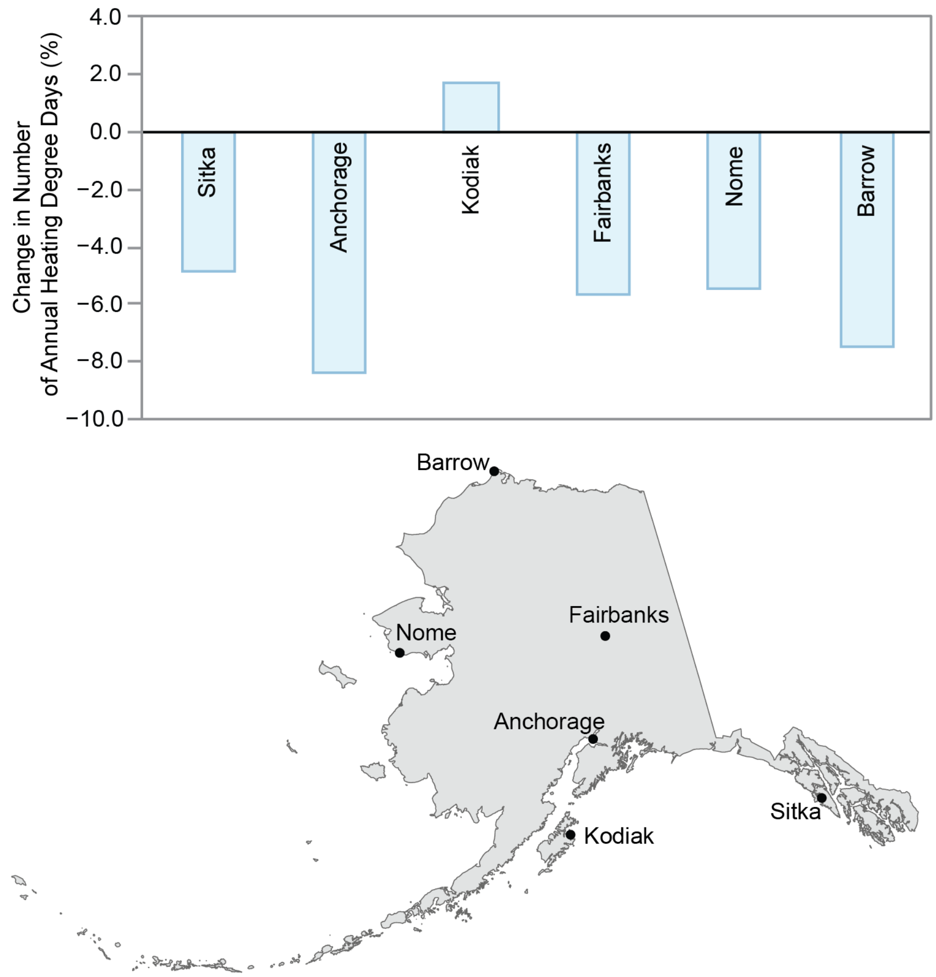


Figure 26.8: The chart shows the percentage change in annual heating degree days for the period 2000–2015 (as compared to 1950–1979) for six Alaska communities. Every 1% decline in heating degree days could potentially yield $10 million of annual savings in heating costs. Sources: University of Alaska Anchorage, NOAA NCEI, and ERT Inc.

Unlike in other regions of the United States, increased cooling degree days (a measure of the energy required to cool homes and other buildings) from warmer summer temperatures provide only a small offset to the beneficial effect of lower heating costs. Applying 2017 retail fuel prices to data on energy use for space heating for Alaska regions, annual expenditures for space heating in Alaska are estimated at about $1 billion (in 2015 dollars).[239,240] Future energy prices are highly uncertain, but the figures suggest that every 1% decline in heating degree days could yield $10 million of annual savings in heating costs.

Key Message 6

Adaptation

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

Alaska and its adjacent Arctic areas are experiencing some of the largest climate changes in the United States (Ch. 2: Climate, KM 7).[14] As such, residents, governments, and industry must prepare for and adapt to the changing climate and associated environmental changes if the most severe impacts are to be avoided.[187,188,241]

Adaptation is often defined as an adjustment in human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects[242] and is an iterative, ongoing process that involves assessment and redirection as needed (Ch. 28: Adaptation).[243] Efforts to prepare for and adapt to the impacts of climate change in Alaska can reduce costs associated with the impacts of climate change,[20,91] generate social and economic opportunities,[244,245] and improve livelihood security.[125,246,247,248] Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change [249] and ocean acidification.[250]

Key elements of successful adaptation in Alaska include coordinated consideration of both environmental and social conditions[134] and careful attention to local context; there is no "one-size-fits-all" strategy.[187,188,251] Enhanced communication, coordination, knowledge sharing, and collaboration are important components of adaptation in Alaska. This includes between communities, among scientists and communities, and across government bodies at the tribal, community, borough, state, and national levels.[251,252,253,254,255,256,257] Building adaptation solutions in partnership with local knowledge is vital for ensuring that adaptations meet local needs and priorities.[254,258,259,260,261]

A range of adaptations to changing climate and related environmental conditions are underway in Alaska, and others have been proposed as potential actions.[135] These adaptations involve human health and poverty alleviation,[136,188] livelihood security,[125] ecosystem management,[262] new construction designs for housing,[263] and a host of other options.[135] Some of these measures reduce vulnerability and risk, while others involve more systemic institutional transformation.[255,260]

At the federal level, there are several key motivations for Arctic Strategies created by various U.S. Government agencies, including 1) recognizing the need to adapt to a changing climate, 2) identifying critical research gaps, 3) creating a vision for regional resilience, and 4) acknowledging the need to safeguard national security under changing environmental conditions.[264,265,266]

Climate change action plans and vulnerability assessments have been completed by several municipalities in Alaska.[135] Formal tribal adaptation planning and preliminary planning activities such as workshops, trainings, webinars, monitoring, and vulnerability assessments have been conducted throughout the state. As of this writing, three climate adaptation plans have been completed and three additional projects are underway to produce climate adaptation plans (Figure 26.9).[8] The Bureau of Indian Affairs awarded eight Climate Resilience Program Awards for adaptation planning between 2013 and 2019.[8] Research has identified 31 adaptation planning-related trainings (2012–2017) and 43 meetings, workshops, and summits (1998–2017).[8] The state-funded Alaska Climate Change Impact Mitigation Program provides funding for hazard mitigation planning, including climate-related hazards such as flooding, coastal erosion, and permafrost thaw.[8,135]

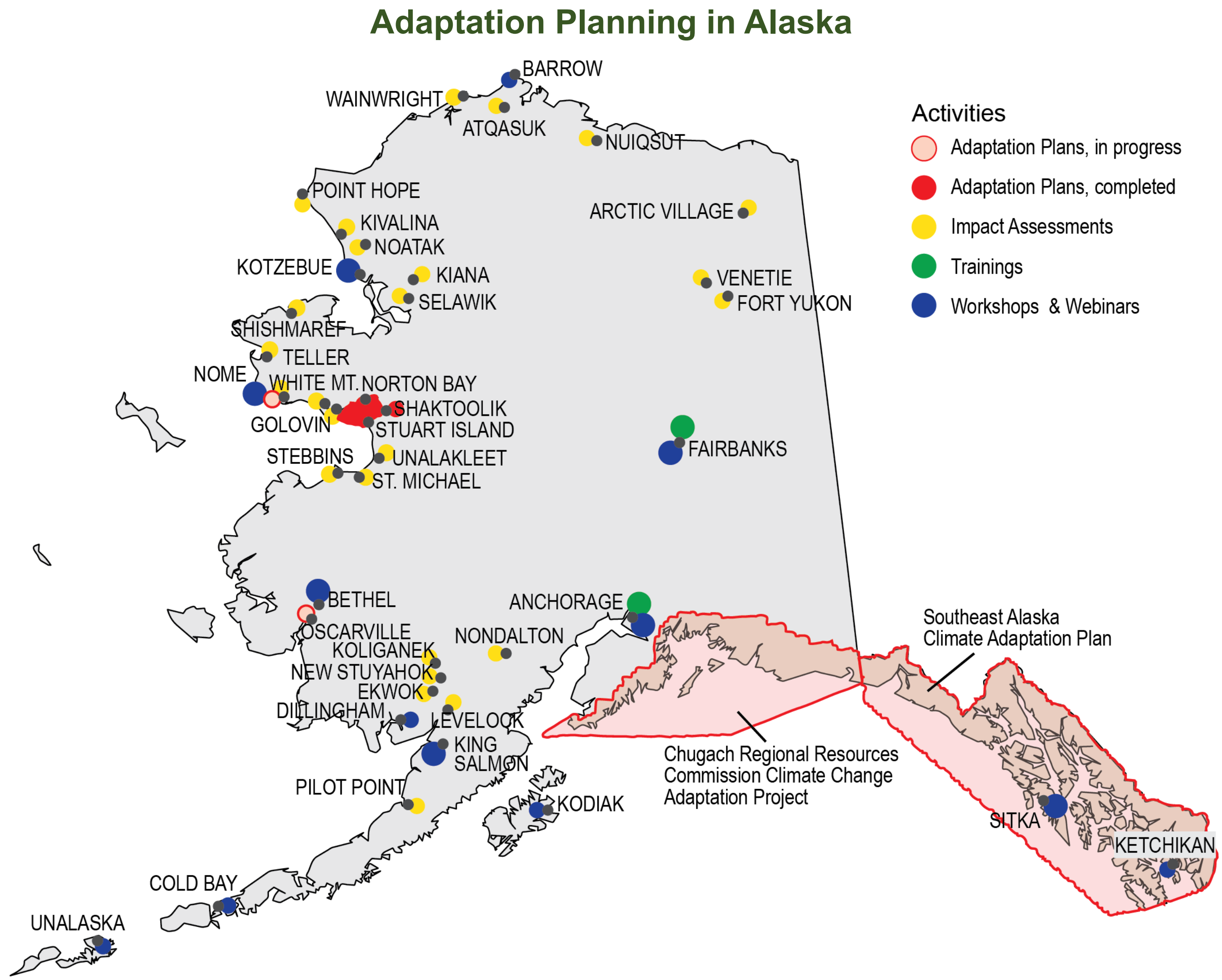


Figure 26.9: The map shows tribal climate adaptation planning efforts in Alaska. Research is considered to be adaptation under some classification schemes.[1,2] Alaska is scientifically data poor, compared to other Arctic regions.[3] In addition to research conducted at universities and by federal scientists, local community observer programs exist through several organizations, including the National Weather Service for weather and river ice observations;[4] the University of Alaska for invasive species;[5] and the Alaska Native Tribal Health Consortium for local observations of environmental change.[6] Additional examples of community-based monitoring can be found through the website of the Alaska Ocean Observing System.[7] Source: adapted from Meeker and Kettle 2017.[8]

In contrast to planning and research, action in response to climate change involves active implementation of plans, changes in policy, protocol, or standard operating procedures, as well as direct reaction to hazards.[135] In the wildfire management and response sector in Alaska, adaptations include establishment of new suppression crew training, evolution of tools used to suppress fire, change in the statutory start date of fire season, and the implementation of community wildfire protection plans.[135]

Several communities in Alaska face immediate threats from climate-related environmental changes, the most severe of which is erosion and coastal inundation related to permafrost thaw and lack of sea ice during fall and winter storms.[122,267] Short-term disaster risk management, such as shoreline revetment, is thus part of adaptation in Alaska.[242] Longer-term planning and village relocation efforts are also underway in two villages but face significant hurdles.[268,269]

Creating decision support tools, establishing climate services and knowledge networks, and providing data sharing and social media have been proposed as additional methods for adapting to the effects of climate change in Alaska.[219,270,271,272,273] Tools that can identify and evaluate policy options under a range of scenarios of future conditions are particularly beneficial in the Arctic, including Alaska.[274,275]

Examples of decision support tools in the state include the Historical Sea Ice Atlas and the SNAP (Scenarios Network for Alaska + Arctic Planning) climate-outlook community charts[276] of projected temperature and precipitation for each community in Alaska. Periodically evaluating decision support tools helps to ensure their usefulness to stakeholders in practical decision contexts.[277]

The use of technology can facilitate the creation and expansion of knowledge networks through events such as webinars[278,279] and social media, such as the newly established AdaptAlaska.org portal and the Local Environmental Observer (LEO) Network that connects people through information, both locally and internationally.[6] Data sharing can be accomplished with online tools such as portals and data hubs; however, the isolated nature of remote, rural communities in Alaska constrains internet connectivity. In addition, technological solutions alone are insufficient to fully meet the information needs of rural communities in the region.[253,271]

A range of climate adaptation guidebooks exist that focus on climate adaptation planning in Alaska and neighboring Canada, which faces related adaptation challenges.[134] These guidebooks have been created by universities, governments, and nongovernmental organizations for a range of audiences, including rural Native Alaska communities, local governments, and state governments. Consistent across the majority of the guidebooks are key phases in the adaptation planning process that include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities (Ch. 28: Adaptation).[134]

Acknowledgments

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Traceable Accounts

Process Description

The Alaska regional chapter was developed through public input via workshops and teleconferences and review of relevant literature, primarily post 2012. Formal and informal technical discussions and narrative development were conducted by the chapter lead and contributing authors via email exchanges, teleconferences, webinars, in-person meetings, and public meetings. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. The author team also engaged in targeted consultations during multiple exchanges with contributing authors, who provided additional expertise on subsets of the Traceable Account associated with each Key Message.

Key Message 1

Marine Ecosystems

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

Description of evidence base

Changes in arctic sea ice and its impacts on marine ecosystems and various biological resources are well documented by 38 years of satellite records[280] and the scientific literature.[48,50,51,77,78,79,281] The finding of a continuing retreat of arctic sea ice is supported by sea ice modeling and continued CO_2 emissions.[37,46] The northward distribution of ocean fish species is documented by numerous scientific papers: see Perry et al. (2005),[282] Thorsteinson and Love (2016),[17] and Mecklenburg et al (2002).[72] The impacts of an increased open Arctic sea contributing to increases in ocean acidification[18] and expanding deeper into the Arctic Basin[57] will need validation with further studies.

Major uncertainties

To date, relatively few of Alaska's marine species have been studied for their response to ocean acidification, and the assessment of potential impacts is challenging due to each species' differing habitats, life cycle stages, and response and adaptation mechanisms. It is known that some organisms respond more dramatically to environmental change than others, and warming ocean temperatures may be more significant in the short term than ocean acidification. There is significant uncertainty in the projected increase of shipping through the Arctic and the Bering Strait, since much of this increase will be driven by economic factors and not climate or other environmental change.

Description of confidence and likelihood

There is *very high confidence* that the arctic sea ice will continue to reduce in size over the next 20–40 years, and it is *likely* that the Arctic Ocean will be nearly ice-free in late summer by mid-century based on current climate models. There is also *high confidence* that this melting will have an effect on the northward expansion of North Pacific fish species and associated effects on associated food webs. There is *very high confidence* that continued melting of the Arctic Ocean ice will have an effect on the habitat and behavior of polar bear and walrus. There is *high confidence* that Alaska's ocean waters are becoming increasingly acidic. Given this increase, it is *very likely* that there will be biological impacts, but it is uncertain which species will be affected and to what extent.

Key Message 2

Terrestrial Processes

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

Description of evidence base

Permafrost

Multiple studies of permafrost in Alaska have shown that the gradual warming of the ground[105] has resulted in the warming and thawing of permafrost over the past 30 years,[79,104,106] and spatial modeling projects that near-surface permafrost will potentially disappear on up to a quarter of the landscape by the end of the 21st century.[108] The magnitude of these changes depends on climate and ground-ice conditions, where permafrost thaw generally results in drier upland habitat and wetter lowlands as tundra and forests are converted to lakes and bogs.[106,283] These changes will undoubtedly result in a number of societal consequences, loss of wildlife habitat, damage to infrastructure (including buildings, airport runways, tank farms, and roads), ecosystem contamination, and increased maintenance costs.[20,21,91,207,284,285]

Wildfire

It has been well documented that wildfires are a common occurrence in Alaska, especially the interior boreal areas, although they have also occurred in areas of arctic tundra,[114,286] with some of the largest fire years (1–6 million acres) occurring between 2004 to 2016 since records began around 1950.[114] Recent studies show that changes in wildfire across the Alaska landscape could be attributed to human activity.[287] This has resulted in changes in boreal vegetation cover[95,96] and tundra communities.[286] The increased fire frequency of recent decades is expected to continue into the future, in spite of the change to less flammable deciduous vegetation, because of the accompanying change to warmer and drier conditions.[95] The ground is warmer under post-fire deciduous vegetation, and thus fires will enhance the thaw of permafrost that is already underway due to climatic warming.[288]

Coastal and River Erosion

The shoreline along Alaska's northern coast has eroded at some of the fastest rates in the Nation, putting local communities, oil fields, and coastal habitat at risk.[19] Unlike the contiguous United States, Alaska is subject to glacial and periglacial processes that make permafrost and sea ice key controlling factors of coastal erosion and flooding. Thermal degradation of permafrost leads to enhanced rates of erosion along permafrost-rich coastal shorelines[19] and subsidence of already low-lying regions. Longer sea ice-free seasons, higher ground temperatures, and relative sea level rise are expected to exacerbate flooding and accelerate erosion in many regions, leading to the loss of more shoreline in the future.[19]

While erosion and changed river courses are a normal part of landscape evolution, lateral river erosion rates are likely to change over time, but the direction and magnitude of these changes are poorly understood. Major river erosion events are typically tied to high hydrological flows or the melting of permafrost along river and stream banks. Statewide, evidence for changes in maximum gauged streamflows is mixed, with a majority of locations having no significant trend.[289] There is significance for seasonal changes in the timing of peak flows in interior Alaska, though increases in the absolute magnitude are not well evident in existing data.[290] Riverine erosion is a serious problem for a significant number of communities.[123] Significant resources have been expended to slow erosion at some communities, often through the construction of berms and bank stabilization projects. These projects have a mixed record of success and nearly always require ongoing maintenance.

Glacier Change

Airborne altimetry surveys of Alaska glaciers spanning the 1994–2013 interval and covering about 40% of the region's glacierized area[137] yield decadal timescale mass balance estimates for individual glaciers and a regional estimate.[291] Several new modeling studies suggest that the measured rates of Alaska ice loss are likely to increase in coming decades,[139,140,141,142] with substantial regional-scale reductions in glacier area, volume (up to 40%–60% loss), and number. Moreover, physically based runoff models suggest that runoff from glaciers accounts for almost 40% of the total freshwater discharge into the Gulf of Alaska.[292]

Interdisciplinary research along the Gulf of Alaska is providing new insights into the role of glacier runoff in structuring downstream freshwater and nearshore marine ecosystems.[101] End-of-century projections from physically based models suggest that anticipated atmospheric warming (2°–4.5°C) will drive volume losses of 32%–58% for Alaska glaciers.[142] Increases in river chemical ions due to glacial runoff and permafrost melt have also been associated with diminishing glaciers in Alaska.[94,291]

Major uncertainties

Some events such as wildfires and coastal storms are dependent on regional and local current weather conditions, and the exact landscape or ecosystem response can be highly variable. Future effects are also dependent on quick response actions and adaptation measures.

Description of confidence and likelihood

There is *high confidence* that wildfire in Alaska will continue but *medium confidence* as to its ultimate effect on vegetation and permafrost, which is often dependent on fire fields available (e.g., older forests or new growth shrublands), the fire intensity, and the return rate. There is *high confidence* that the north coast of Alaska is eroding at high rates. It is *likely* that coastal erosion is accelerating in response to climate change but *medium to low confidence* as to the location and rate because of limited studies and datasets documenting this. There is *high confidence* that river erosion will continue but *medium confidence* as to when, where, and to what extent this will occur across Alaska because of differences in local climatic and geographic qualities of the area in question. There is *high confidence* and it is *likely* that the glaciers in Alaska will continue to diminish, especially those that are tidewater glaciers.

Key Message 3

Human Health

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

Description of evidence base

The evidence base for climate-related health threats can be divided into three main categories. First are those threats that have strong documentation of both the climate or environmental driver and the health effect. An example is the emergence of gastrointestinal illness due to the northward expansion of the bacteria *Vibrio parahaemolyticus* among Alaska shellfish. Other threats with a similar level of evidence include increased venomous insect stings.

Second, some health threats are based on a combination of well-documented climate-driven environmental changes and records of anecdotal community observations of health impacts. Examples include the increased risk of injury or death from exposure among winter subsistence-related travelers or respiratory problems from smoke inhalation during wildfires. The community observations of these threats point to a real trend.[10,158] However, there is no historical or current means to document and track such injuries or exposures. Therefore, objective evidence, such as increased rates of occurrence or peer-reviewed reports, is not currently available. Other threats that fit this category include respiratory symptoms from dust and pollen, decreased food security, and loss of cultural and traditional lifestyles and practices along with the accompanying mental health or social disruption effects.

The third category is those threats that are logical inferences of potential health risks based on documented environmental changes and community-vulnerability assessments. Examples include the well-documented threats from coastal storms to community infrastructure and shorelines and the damage to community water and sanitation systems from permafrost thawing or erosion. The risk of physical harm from major storm or flooding events is obvious, and the loss of a water/sewer system would likewise pose a clear threat to health through waterborne or water-washed infections. However, these threats are based on likely outcomes from existing trends in environmental change. The human health effects are either undocumented or are anticipated in the future. Many of the infectious disease risks and harmful algal blooms (HABs) fall into this category; where range expansion of pathogens or vectors is occurring, health effects are likely to follow.

Major uncertainties

The greatest uncertainties in the health threats of climate change lie in the geographic distribution, magnitude, duration, and capacity to detect the effects. Many of the impacts of climate changes are most evident in rural Alaska, which is an enormous area and sparsely populated. Thus, sporadic events with geographic variability such as storms or HABs may have a range of human health effects from none to severe, depending on the timing and location of exposure. Likewise, the magnitude and duration of the effects on health are difficult to predict based on variability in the source of risk and human adaptation. The lack of repeated outbreaks of V. *parahaemolyticus* illnesses from raw shellfish consumption is a good example of how adaptations in aquaculture practices and commercial regulations, along with likely changes in consumer practices, appear to have reduced the magnitude of the health threats, compared with initial outbreak. Finally, we have limited capacity to detect many of the health outcomes associated with climate change. The organized reporting and monitoring of climate-linked health effects by public health are limited to the toxin-mediated illnesses, some of the infectious diseases, mortality events, and unusual clusters of illnesses or injuries. Even among those conditions, underreporting of illnesses is common due to healthcare-seeking behavior, lack of recognition by medical providers due to unfamiliarity or limited diagnostic capacities, or incomplete compliance. For many of the anticipated health effects, such as nonoccupational injuries, mental health issues, and respiratory conditions, there may be documentation in a person's individual health records, but no systems are in place to collect such information and link these illnesses to climate or environmental events or conditions. Large administrative healthcare databases, such as the Alaska Hospital Discharge Data System or the Alaska Health Information Exchange, could be used for focused investigations or ongoing monitoring. However, these would only be useful for severe illnesses with large geographic or multiyear distributions. These datasets would likely miss health events that do not result in emergency room visits or hospitalizations, that are rare, or that occur in irregular episodes. Data from ambulatory clinic visits, community surveys, or syndrome-based surveillance efforts would be needed to detect and characterize uncommon or less severe health occurrences.

Description of confidence and likelihood

There is *high confidence* that there will be a continuation of trends causing higher winter temperatures, increased storm events, increased frequency and extent of wildfires, and increased permafrost thawing with associated erosion. Given these trends, there is *very likely* to be subsequent human health effects, but the distribution and magnitude of these effects remain uncertain.

Key Message 4

Indigenous Peoples

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

Description of evidence base

Many studies have examined different aspects of Alaska's Indigenous communities, including the ways climate change is affecting or can affect subsistence,[15,26,28,29,30,125,131,194,197,198,293] culture,[125,182,184] health,[27,29,294] and infrastructure.[20,21,164,295] Alaska's Indigenous peoples are increasingly involved in the research efforts, not just as informants or assistants but as those shaping and asking research questions and as those analyzing and interpreting the results of studies.[27,29,125,190] As a result, research on the impacts of climate change on Alaska's Indigenous peoples is increasingly focused on topics of direct relevance to daily lives and long-term/historical interests and is increasingly attentive to the context in which those changes occur. In other words, there is increasing confidence that the right questions are being asked and the answers are being interpreted in the right way.[29,125]

Major uncertainties

There is little question that climate change is having widespread and far-reaching impacts on Alaska's Indigenous peoples. It is less clear, however, exactly which peoples and communities are responding to the changes they face. One community may be able to seize a new opportunity or may be able to adjust effectively to at least some forms of change, whereas another community will not be able to do either. More needs to be understood about these differences, the reasons for them, and how adaptability and resilience can be fostered.

It is also unclear how, exactly, the changes will influence one another as they occur in the context of all that is happening in Alaska Native life. For example, climate change may mean hunters have to travel farther to hunt. GPS allows for more reliable navigation, and four-stroke engines provide more confidence when traveling farther offshore. At the same time, rising fuel prices mean it is more expensive to travel far, perhaps limiting the ability of a hunter to take advantage of better navigation and motors. How these competing influences will balance out is difficult to say and requires more attention.

Description of confidence and likelihood

There is *high confidence* that climate change is having far-reaching effects on Alaska's Indigenous peoples. It is *likely* that most of these impacts will have negative effects, as they undermine existing behaviors, patterns, infrastructure, and expectations. It is also *likely* that there will continue to be some benefits and opportunities stemming from climate-related changes. There is *medium confidence* that the negative impacts can be reduced and the new opportunities maximized with appropriate policy and regulatory action, as not all aspects of change can be addressed in this way, and it is unclear whether such a systematic approach is plausible in light of the way programs and policies are administered in Alaska's Indigenous communities.

Key Message 5

Economic Costs

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

Description of evidence base

Coastal erosion affects a number of coastal communities, with the highest rates on the Arctic coastline.[19] Coastal erosion and flooding in some cases will require that entire communities, or portions of communities, relocate to safer terrain. The U.S. Army Corps of Engineers identified erosion threats to 31 communities requiring partial or complete relocation.[123] Relocation costs for seven vulnerable communities identified in a 2009 U.S. Government Accountability Office (GAO) study ranged from $80 to $200 million per community.[122]

Melting glaciers will increase the role of seasonal precipitation patterns for hydroelectric power generation. River discharge has been increasing during the winter since the 1960s, but because reservoirs are generally full in fall, investments to increase reservoir heights would be required to take advantage of increased fall precipitation.[145]

National Weather Service (NWS) daily weather summaries show that heating degree days have already declined by 5% in Sitka, 6% in Fairbanks and Nome, and 8% in Anchorage and Utqiaġvik (formally known as Barrow) as compared to mid-20th century levels. The same NWS data show that increased cooling degree days from warmer summer temperatures provide only a small offset to the beneficial effect of lower heating costs.

Major uncertainties

The extent, rate, and patterns of coastal erosion at locations other than along the north coast, and including deltas and rivers, are poorly known. Change in the patterns and trends of erosion (for example, an increase in the rate associated with warming and climate change), is expected but poorly documented for most locations due to the scarcity of historical data.

Future energy prices are highly uncertain, generating a high level of uncertainty around the dollar value of the savings in space heating costs associated with the projected decline in heating degree days.

Wildfire suppression costs depend on future policy decisions for wildfire management. Property damage from wildfire depends on uncertain future settlement and development patterns.

Description of confidence and likelihood

There is *high confidence* and it is very likely that future damage to infrastructure from thawing permafrost and coastal erosion will cost hundreds of millions of dollars annually to repair or replace. There is *high confidence* and it is *likely* that timely repair and maintenance of infrastructure can reduce damages and avoid some of the added costs. There is *medium confidence* and it is *very likely* that these costs will be offset in part by savings from reduced space heating needs.

Key Message 6

Adaptation

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

Description of evidence base

Research investigating costs of adapting to projected climate changes in Alaska in the realms of public infrastructure and wildfire suppression indicates cost savings from adaptation.[21,91] Rural Alaska communities have high reliance on subsistence food resources. Access to these resources, as well as their habitat and migration patterns, is impacted by several factors, including climate change. Adaptation is thus important for maintaining livelihood security in these communities.[125,246,247,248] Vulnerability analyses of Alaska communities indicate adaptation as a key element to address high vulnerabilities to biophysical impacts of climate change[249] and ocean acidification.[250] Rural communities in Alaska share many climatic, cultural, and ecosystem properties with rural communities across the Arctic. Research in Canada has documented the social and economic opportunities from adaptation in Northern communities.[244,245]

Adaptation actions to the impacts of climate change in Alaska have been transitioning from awareness and concern to education and actions.[135,251] There are a number of documents that describe climate change related research needs and actions associated with infrastructure, economics, hazards and safety, and terrestrial ecosystem impacts, as well as other concerns of rural Alaska Native communities.[8,135,252,271] Adaptation actions that address these same needs have also been described in Canada and the circumpolar Arctic.[135] The importance of direct engagement and partnership with communities in adaptation is emphasized throughout the literature.[125,187,205,252,253,254,258,259,260,261,271,296,297]

Most research reports on case studies and actions that describe transparent, collaborative, and accessible information though data sharing, building of networks, and long-term partnerships with communities.[252,253,254,260,261] Climate change has also been described as a risk management problem, with proposed actions that address risk and inform risk management actions being offered.[255]

A number of climate adaptation guidebooks focus on Alaska and Canada, which have related adaptation challenges.[134] Universities, governments, and nongovernmental organizations produced these guidebooks for a range of audiences, including rural Alaska Native communities, local governments, and state governments. Key phases in the adaptation planning process that are consistent across the majority of the guidebooks include building partnerships and networks of stakeholders; conducting vulnerability and risk assessments; establishing priorities, options, and an implementation plan and evaluation metrics; implementing the preferred option; and conducting ongoing monitoring and adjustment of activities.[134] Guidebooks specific to Alaska Natives and Canadian Inuit and First Nations peoples emphasize the importance of community support and participation in the adaptation planning process.[134]

Major uncertainties

Little research has been conducted to track and evaluate the efficacy of implementation of existing adaptation planning in Alaska or to assess the possibilities for maladaptation. Similarly, the feedbacks and synergies are not well documented between adaptation and changes in physical, natural, and social systems. More research is needed to understand cross-sector and cumulative impacts and how they can best be addressed in an all-inclusive manner.[135]

Description of confidence and likelihood

There is *high confidence* that proactive adaptation can reduce costs, generate social and economic opportunity, and improve livelihood security. It is *likely* and there is *high confidence* that proactive adaptation will be affected by external factors, such as global markets that are beyond the control of the organization or institution implementing the adaptations.

It is *likely* and there is *very high confidence* that direct engagement and partnership with communities will be a critical element of adaptation success, as this has strong evidence and high consensus in the literature; however, there are a limited number of publications that document this partnership model in Alaska.

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